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Review

Let's Get Real: Are Wearable Plant Sensors Ready for Crop Monitoring?

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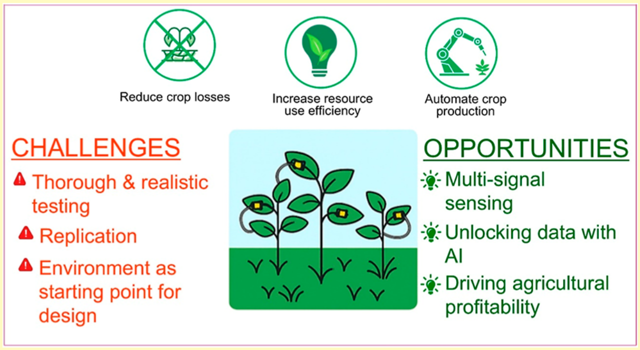
ABSTRACT: In recent years, the number of publications describing new and exciting developments in wearable plant sensors (WPSs) has skyrocketed. These small, lightweight sensors hold promise to assist precision agriculture and may thus help reduce crop losses, increase resource use efficiency, and automate crop production. However, WPSs are often not adequately tested in environments relevant for crop growth, and the majority of experimental WPS studies reveal a glaring lack of basic knowledge of plant biology. This review aims to bridge the communication gap between WPS developers and the wider plant research community by (1) providing essential physiological and environmental background information for engineers in relation to WPS sensing capabilities, (2) offering a step-by-step guide to conduct sensor tests on plants correctly, and (3) highlighting potential challenges and suggesting WPS applications in the open field, greenhouses, and vertical farming systems. We hope this review facilitates the development of WPSs and guides them to be truly "ready for the world".



KEYWORDS: *experimental setup, plant wearable sensors, plant−environment interactions, physiology, stress detection, wearable plant sensors, crop monitoring, precision agriculture, sensor validation*

Wearable plant sensors (WPSs) are a relatively recent group of sensors that, as the name implies, are directly attached to the plant. Unlike many other sensing approaches, including portable handheld devices, WPSs are typically small, flexible, and unobtrusive, making them ideal candidates for crop monitoring.[1,2] Depending on the type of sensor, WPSs measure signals on or just under the surface of a plant organ. These signals are related to various aspects of plant growth, physiology, microclimate, and the presence of pesticides. Whereas many rapid phenotyping approaches are noncontact, imaging, or laser-based methods[3−5] and quantify traits that are often related to plant morphology, WPSs can actually inform on plant physiology in relation to the plant's dynamic growing environment.

WPSs have enormous potential: they may become very cheap, small, lightweight, and self-powered (Figure 1), which would enable their widespread use globally. Furthermore, WPSs can measure a large range of signals that are generated internally and externally, i.e., signals that are relevant to key processes of plant physiology, as well as the environmental factors that drive these processes (Figure 1). Given that agriculture faces problems that are partially related to inefficient use of land, water, and agrochemicals, as well as population growth, land degradation, disease pressure, and climate change, new and affordable monitoring techniques that can enable greater precision agriculture are needed. The use of WPSs may help enable an "internet of plants"[6] that might revolutionize precision agriculture across different production systems, including vertical farms, greenhouses, and open fields. However, the added value, reliability, and durability of WPSs in these production systems remain to be demonstrated.

Within the last ten years, the relevance of WPSs in the scientific literature has been growing strongly, both in numbers of experimental studies reporting on novel WPSs (Table S1) and in numbers of literature reviews (Table S2) on the topic (Figure 2). These rapid developments of WPSs seem to be driven largely by developments of flexible, wearable, and small sensors in other fields of electrical engineering, especially in application to humans. Consequently, many laboratories working on WPSs are strongly focused on the engineering aspects of the sensors themselves but seem to be much less focused on (proper) testing of WPSs on plants in realistic settings (despite the explicit claim made in many publications that these sensors should aid precision agriculture in the field).

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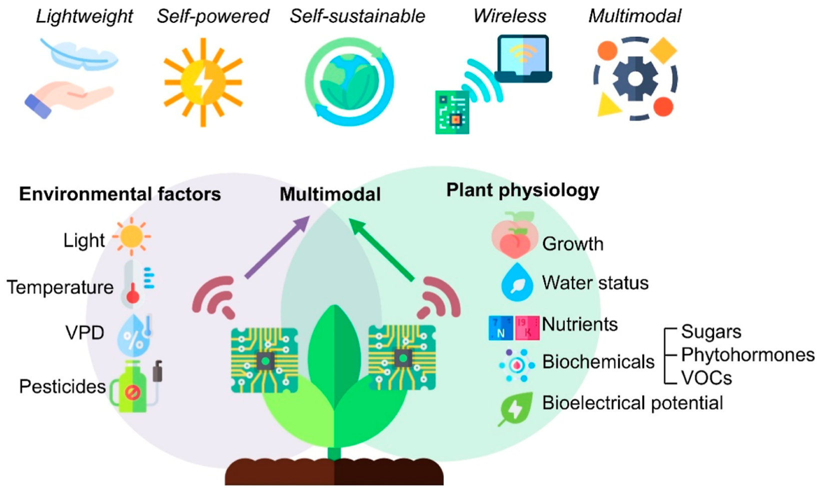

Figure 1. Schematic of idealized WPS properties (in italics) and the various signals they can measure. Each icon was sourced from Freepik (https://www.freepik.com/).

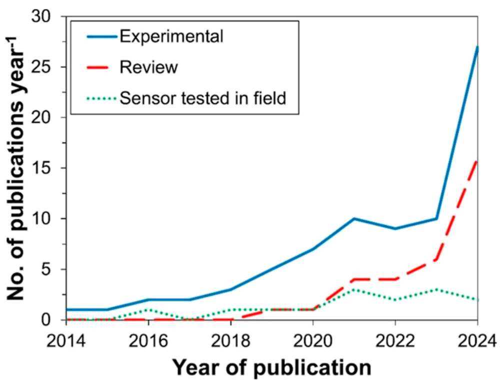

Figure 2. Growing relevance of wearable plant sensors, as reflected in the number of publications per year (2014–2024). The numbers of literature reviews, experimental studies, and experimental studies actually testing the sensors in the field are shown. All studies included here are listed in Tables S1 and S2, and details on the literature search and selection criteria can be found in supplementary methods 1.

For example, we found that only 15 out of 93 experimental studies—16%—actually tested their sensors in the field (Figure 2, Table S1); among these, field testing was conducted for 48 h only (median value; range: 2.5 to 960 h; Table S1), suggesting that longer-term testing of sensor functioning in the relevant production environment(s) is very scarce. Indeed, many authors seem to be entirely uncritical with regard to the practicality of sensor deployment in crop production systems; for example, in only 32% of studies was a proper sensor cross-validation conducted when the WPS was measuring on a plant (Table S1). This is problematic, as eventual use in the crop production environment necessitates proper testing in that environment. Also, the lack of proper testing introduces an unnecessary divide between WPS developers and the supposed end users, among whom are farmers, agronomists, plant breeders, and plant scientists. The lack of proper testing hinders the practical adoption of these technologies, reducing applicability in actual agricultural environments and slowing much-needed technological development. In this review, we aim to bridge these gaps by (a) highlighting the novel properties and opportunities that various WPSs offer in relation to plant ecophysiology, (b) identifying the common mistakes (or pitfalls) in current WPS testing on plants, and (c) assessing the viability of WPSs in different production environments. Furthermore, we provide developers with a point-by-point protocol for proper WPS testing from a plant science point of view (Table 2). We argue that in order for the WPS research field to mature, stringent validation of WPSs in the real world and (at least) a basic understanding of plant ecophysiology are crucial.

Table 1. Optimal Growth Conditions for Several Major Food Crops Grown in the Field (Wheat, Maize), Greenhouse (Tomato), and Vertical Farms (Lettuce)[a]

Crop	T-Day (°C)	T-Night (°C)	DLI (mol m^{-2} d^{-1})	RH (%)	photoperiod (h)	irrigation needs	nutrition needs	references
Wheat	18–24	12–18	12–20	40–60	Long-day (12–16)	Moderate, avoid drought	Balanced N–P–K, good N supply during vegetative growth	127,128
Maize	24–30	18–22	20–30	40–60	Neutral (12–14)	High, consistent moisture, avoid waterlogging	High N requirement, adequate P & K for rooting and kernel filling	129,130
Tomato	22–28	16–18	20–30	60–70	Neutral (12–14)	Frequent, moderate	High K during fruiting, adequate Ca to prevent blossom-end rot	131–133
Lettuce	18–22	12–16	12–17	50–70	Long-day tolerant, but short days delay bolting	Frequent, shallow-rooted, steady supply	Moderate N for leaf growth, avoid excess (causes tipburn and bolting)	134–136

[a]Abbreviations: DLI, daily light integral; RH, relative humidity; T-Day, temperature during the day; T-Night, temperature during the night.

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2. IMPORTANT SIGNALS AND THE WPS TO MEASURE THEM

A diverse array of WPSs has been developed to monitor a broad spectrum of environmental factors and signals related to plant physiology. In this section, we introduce the signals most commonly measured by WPSs and their relevance for understanding key plant−environment interactions.

2.1. Environmental Factors. *2.1.1. Light.* Light is indispensable for plants, as both a source of energy and of information. As photoautotrophs, plants require photosynthetically active radiation (PAR; 400−700 nm) to power photosynthesis and thus growth. The total amount of PAR received per day (daily light integral, DLI; Table 1) is a strong driver of plant growth. Additionally, the spectrum of light that they receive drives photoreceptor action, which affects plant morphology, development, and consequently growth: for example, two plants receiving the same PAR intensity but different spectral distributions can look very different, resulting in vast differences in plant growth due to differences in light interception.[7] Furthermore, the duration of illumination per day (photoperiod) and the pattern of light intensity during the photoperiod also influence plant growth. Despite the central importance of light intensity, spectrum, duration, and pattern for plants, these are very rarely controlled, measured, or (correctly) reported in experimental WPS papers. For example, we found that while some papers did not describe the light environment at all (e.g., refs 8−10), others used the unit lux (e.g., refs 11 and 12) to report the light intensity measured. However, lux is focused on human eye sensitivity and is unsuitable in relation to plants; the appropriate unit to quantify light intensity as it relates to plants is photosynthetic photon flux density (PPFD; μmol photons m^{-2} s^{-1}). Lux can be converted to PPFD, but the conversion factor depends on the light source, and examples can be found in Thimijan and Heins,[13] Ahn et al.,[14] and Javed et al.[15]

2.1.2. Temperature. Temperature drives plant development and affects the rate of virtually every process in plants. Optimal temperature varies depending on plant species: for example, cowpea (*Vigna unguiculata* L. Walp) grows well at around 30 °C, with photosynthetic activity remaining stable up to 45 °C.[16] Cowpea is highly sensitive to chilling stress at just below 20 °C,[17,18] whereas the model plant *Arabidopsis thaliana* is more tolerant to chilling but less tolerant to heat. Thus, when conducting physiological tests on WPSs, it is important to consider the temperature, both when growing the plants and when conducting measurements on them. However, many studies overlooked its effects when testing WPSs, and they often do not describe temperature conditions. Regarding temperature sensing, air and leaf temperature (T_{leaf}) differ frequently, and for many applications, it is useful or even crucial to measure both. When combined with other sensors, temperature sensing offers valuable insights into how plants grow and respond to their environment, including stress.[19]

2.1.3. Vapor Pressure Deficit (VPD). Vapor pressure deficit (VPD) represents the difference between saturation vapor pressure at T_{leaf} and actual vapor pressure and thus indicates the driving force of transpiration (Broughton and Conaty, 2022). To calculate VPD, T_{leaf} and relative humidity (RH) sensors are required.[20] Under high VPD, stomata close to conserve water, thereby reducing CO_2 intake and limiting photosynthesis and plant growth. Based on a 40 day field experiment on bell pepper plants under control and water-stressed conditions, Hossain and Tabassum[19] reported a significant increase in VPD after at least 5 days, suggesting that VPD measurements over a minimum of 5 days may have the potential to detect plant stress conditions. For a reference on optimal growth parameter ranges for key field, greenhouse, and vertical farm crops, see Table 1.

2.1.4. Pesticides. Several approaches were developed to detect a range of insecticides (methyl parathion and dimethoate), fungicides (carbendazim), and herbicides (paraquat, diquat). Cyclic voltammetry (CV) was used for methyl parathion and nitrite detection.[21,22] Differential pulse voltammetry (DPV) and square wave voltammetry (SWV) were used to detect carbendazim, diquat, and paraquat.[23,24] Zhang et al.[25] employed DPV in their self-powered sensor to detect methyl parathion. In contrast to these electrochemical approaches, Qiu et al.[26] explored field-effect transistor technology to detect dimethoate.

Most studies presented only simple measurements of pesticide residues on plant surfaces.[21−23,25,26] Teixeira et al.[24] presented a refreshing exception to this, as they included washed and soaking tests, indicating a consideration for pesticide residues, which may provide a more realistic assessment of pesticide presence over time or within the sample matrix.

There are several considerations when developing and implementing pesticide monitoring in WPSs. For example, selectivity and cross-reactivity are crucial because sensors must accurately detect target pesticides amid complex matrices. Matrix effects, including plant surface components, humidity, and other environmental factors, can also affect sensor readings and thus must be carefully managed. Calibration and standardization protocols are essential as are durability and cost-effectiveness. To realize the full potential of pesticide-monitoring WPS, tests should incorporate physiologically relevant testing to validate the sensor performance in real-world scenarios.

2.2. Plant Physiology. *2.2.1. Growth.* Growth, resulting from cell division and expansion, can be monitored macroscopically through the elongation of plant organs. Piezoresistive sensors, which measure changes in electrical resistance due to mechanical stress,[27−30] are often used for this purpose. The data obtained from strain sensors can be used to monitor fruit growth, which can help predict harvest time. However, sensor effectiveness can be influenced by sensor stretchability and placement, interference from environmental factors, and the potential impact of the sensor itself on plant growth.

2.2.2. Water Status. Water plays key roles in photosynthesis, nutrient movement, cell turgor pressure, and self-cooling via transpiration.[31,32] Water status shows how these processes work together—from absorption in the root zone, through transport in the xylem (sap flow), to the release of water vapor through transpiration.[33,34] Leaf surface humidity (LSH) partially reflects transpiration, although air humidity and temperature also influence it.[35] Stomata regulate the balance between the uptake of carbon dioxide (CO_2) for photosynthesis and the release of water vapor. LSH can be affected by various abiotic stresses, such as temperature fluctuations and osmotic stress induced by salinity and drought;[36] thus, careful consideration of these factors is required for accurate interpretation. LSH can be measured through capacitance changes between two electrodes, which signals the presence of water droplets.[37,38] Leaf RH can also be measured based on electrical resistance.[39] Further, impedance

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spectroscopy can provide information about leaf wetness and water content.[40−42] Sap flow can be sensed through the heat pulse[43] and the heat dissipation methods,[44] which are based on measurements of spatial anisotropy in thermal transport within the plant. Furthermore, temporal variations in stem diameter have been used to quantify sap flow.[45,46]

Both LSH and sap flow measurements can provide valuable information for identifying water stress and optimizing irrigation schedules.[47,48] However, to put water status into context, factors, including air temperature and humidity, should be measured alongside water status. Additionally, the impact of sensors that block stomata and heat pulses on long-term physiological responses should be considered.

2.2.3. Nutrients. Nutrients are essential for plant growth. Primary macronutrients include nitrogen (N), phosphorus (P), and potassium (K), while secondary macronutrients consist of calcium (Ca), magnesium (Mg), and sulfur (S). Micronutrients, or trace elements, include iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), chlorine (Cl), and molybdenum (Mo) (Mohr and Schopfer, 1995).

Among these, N and K have received the most attention in WPS development. Nitrogen is crucial for growth as a key ingredient of many proteins and chlorophylls;[49] nitrogen-deficient plants exhibit stunted growth, yellow leaves (chlorosis), and reduced vigor.[50] Potassium regulates water and nutrient transport, enzyme activation, and protein synthesis.[51,52] Lack of potassium leads to weak stems, yellowing or necrosis along leaf edges, and increased susceptibility to pathogens, as well as poor water retention and nutrient uptake.[53] Nitrogen is primarily taken up as nitrate (NO_3^-) or ammonium (NH_4^+), and potassium is absorbed as K^+ ions. Correspondingly, several wearable and implantable sensors have been developed for these nutrients. For nitrogen, microneedle-based nitrate sensors[54] and solid-contact ion-selective electrodes for NO_3^- detection in plant sap[55] have been reported, alongside the IoTree system capable of tracking NH_3 levels within the xylem.[56] For potassium, recent efforts include a wearable film sensor monitoring K^+ leached from leaves,[57] a dual microneedle sensor for simultaneous K^+ and Na^+ detection,[58] an OECT-based implantable sensor for in vivo K^+ monitoring,[59] and the IoTree device for K_2O detection in xylem sap.[56] These capabilities highlight the promise of the WPS in supporting irrigation and fertilization management.

Beyond N and K, other essential nutrients were also explored. Calcium plays a fundamental role in cell wall stability and intracellular signaling, and Kim et al.[55] demonstrated a potentiometric ion-selective electrode for Ca^{2+} detection in plant sap. Zinc, a critical cofactor for many enzymes and regulatory proteins, has been targeted with a needle-type microsensor capable of detecting Zn^{2+} uptake and transport in citrus leaves.[60] While reports for other macro- and micronutrients remain scarce, these initial demonstrations suggest that WPSs can be extended to a broader range of nutrient signals. A comprehensive summary of reported nutrient-related WPSs is provided in Table S3.

2.2.4. Biochemical Signals. Biochemical signals, such as sugars, phytohormones, and volatile organic compounds (VOCs), are central to regulating plant growth, defense, and stress adaptation. Wearable plant sensors (WPSs) have recently been developed to enable their nondestructive, in situ monitoring, providing opportunities to monitor biochemical signals to understand plant physiological responses.

2.2.5. Sugars. Through photosynthesis, plants absorb CO_2 and subsequently synthesize sucrose and starch, which undergo further differentiation. Apart from fueling plant growth, sugars play a critical role in the plant's response to environmental stressors. Sugars can alleviate stress by facilitating osmotic regulation or serve as substrates for the scavenging of reactive oxygen species (ROS). Several WPSs exist for glucose[61−63] and glucose plus sucrose monitoring,[64] using enzymatic methods. These approaches used microneedle-based sensors,[61,63] magnetic sensors,[62] and implantable organic electrochemical transistors (OECTs),[64] respectively. Applications of real-time sugar content monitoring can provide insights into plant stress responses and metabolic dynamics. For example, Perdomo et al.[62] demonstrated the use of such sensors to monitor stress responses in leaves, while Diacci et al.[64] investigated sugar homeostasis in the vascular tissues of trees. Further developments of such sensors should consider enzyme stability, plant wound responses, and potential interference from compounds that plants naturally produce such as hydrogen peroxide.

2.2.6. Phytohormones. Phytohormones such as abscisic acid (ABA), salicylic acid (SA), and indole-3-acetic acid (IAA), which exist in a dissolved state in the plant's fluids, regulate many processes related to growth, development, and responses to environmental stimuli. ABA specifically regulates responses to drought and osmotic stress,[65] among others. SA regulates responses to biotic (e.g., pathogen attack) and abiotic stress (e.g., drought, salinity).[66−68] IAA is primarily associated with auxin signaling, affecting growth processes such as cell elongation and lateral growth.[69] For example, with salt or heavy metal stress, IAA levels can increase and influence auxin transport or growth patterns, helping the plant adapt.[69−71] Various WPSs have been developed to sense ABA,[72] SA,[9,19,62,73] and IAA.[74]

Ethylene is the only gaseous phytohormone and is produced under stress, including flooding, drought, wounding, pathogen attacks, and mechanical stress,[75] as well as fruit ripening. Measuring ethylene concentration may help detect water stress, as a 40 day field experiment on bell pepper plants showed a significant increase in ethylene under water stress within 1 day.[19] Ethylene interacts with other phytohormones to coordinate stress responses[76,77] and exhibits quicker spikes compared to other hormones. Since ethylene is gaseous, it can be monitored relatively easily. Ethylene measurement is also applied to fruit ripening control and postharvest storage management.

In terms of sensing principles, ABA has been detected using nanostructured microneedle electrodes that directly catalyze ABA oxidation.[72] For SA, different strategies have been demonstrated: nanomaterial-based electro-oxidation on flexible electrodes,[73] molecularly imprinted polymers combined with impedance and amperometry,[9] and reverse iontophoresis with laser-induced graphene electrodes for noninvasive extraction.[78] A multimodal platform integrating SA and ethylene sensing has also been reported, where SA was detected electrochemically via DPV, while ethylene was measured using copper-based nanostructured electrodes with CV responses characterized under graded ethylene gas concentrations.[19] IAA has been measured electrochemically via its oxidation peak on nanostructured electrodes.[74] These examples illustrate how recognition strategies—ranging from catalytic surfaces to molecularly imprinted polymers—translate the hormone presence into measurable signals. Additional details and

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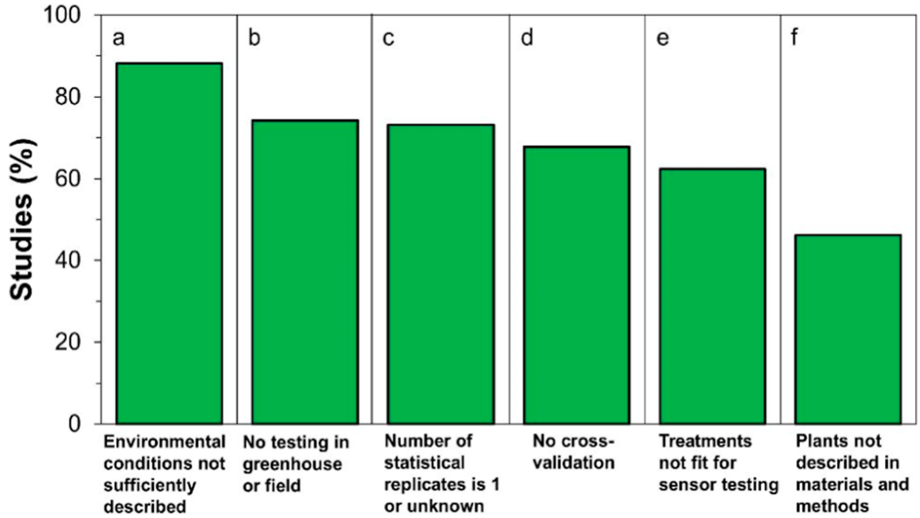

Figure 3. Common problems in studies testing wearable plant sensors on plants, ranked by occurrence of problem. These include the following: (a) the description of environmental and other conditions relevant to plant physiology during plant cultivation and/or during experiments was nonexistent or inadequate; (b) the sensor was not tested in the greenhouse or the field (only in the lab or in a climate chamber); (c) the number of biological replicates was either 1 (n = 1) or not clearly mentioned; (d) while it was attached to the plant, data generated by the sensor was not cross-validated using any other (standard) measurement; (e) either no specific treatment was applied or the applied treatments were not adequate for testing the functioning of the sensor on the plant; and (f) in the materials and methods section, plant material was either not mentioned at all or was described so superficially that it would be impossible to replicate the study. The total number of experimental studies included is 93, and the studies were published between 2014 and 2025. For details, see Table S1 and supplementary methods.

comparisons of reported platforms are summarized in Table S4.

Despite the promise shown by WPS studies in monitoring phytohormones for the detection of abiotic or biotic stresses,[9,19,78] the complex mechanisms governing plant hormone responses and the intricate crosstalk between them highlight the critical importance of establishing the physiological relevance of measurements for developing effective phytohormone detection sensors. This requires a comprehensive understanding of the sensing mechanism and thorough testing to ensure accurate and reliable data.

2.2.7. Volatile Organic Compounds (VOCs). Plants emit a wide range of VOCs, including terpenoids, aromatic compounds, fatty acid catabolites, and amino acid derivatives produced via the shikimic acid pathway.[79,80] VOCs are induced and emitted under abiotic and biotic stresses (e.g., defense against herbivores or pathogens).[81] While few WPS for VOCs exist, among them are two sensors developed to detect methanol.[54,82] Methanol can act as a signaling molecule,[83] and its production increases under stress.[84] Both sensors employed a chronoamperometric response mechanism using slightly different materials, and their specificity for methanol detection was tested. However, sensor data showed large discrepancies from gold standard measurements (in this case, gas chromatography−mass spectrometry) and experimental setups that were largely irrelevant. Moru et al.[82] attempted to measure methanol levels at different developmental stages of maize, while Ibrahim et al.[54] examined two maize genotypes. Neither study investigated methanol responses to abiotic or biotic stresses; we suggest that further testing under relevant experimental setups is required. Another WPS differentiated 13 different VOCs with >97% accuracy through chemiresistive measurements.[85] This sensor was able to diagnose tomato late blight as early as 4 days postinoculation with *Phytophthora infestans* and detect abiotic stress (mechanical damage) within 1 h. However, the mechanism by which this sensor differentiates between mechanical and biotic stresses requires further investigation. In addition, another VOC sensor developed by Wang et al.[86] can differentiate eight distinct VOCs and distinguish three wheat pathogens (*Fusarium graminearum*, *Nigrospora rubi*, and *Fusarium pseudograminearum*) by incorporating PCA analysis.[86]

While VOC monitoring can offer early indicators of environmental stress, several key considerations must be addressed. Given the low concentrations and complex mixtures of various VOCs, sensors must be both highly sensitive and specific. For real-time monitoring, rapid and reversible responses to VOC concentration changes are essential as is long-term stability. Regular calibration against known standards is likely required to ensure reliable readings. Finally and crucially, establishing a clear link between VOC emission changes and specific physiological processes or stress responses is paramount to enable a mechanistic understanding.

2.2.8. Bioelectric Potential. Bioelectric potential, or biopotential, is an electrical signal generated by ion movement across cell membranes.[87] Key ions are K^+, H^+, Cl^-, Ca^{2+}, Na^+, and Mg^{2+}, which move between, e.g., chloroplasts, guard cells, the plasma membrane, vacuoles, the xylem, and roots.[88] Measuring bioelectric potential can help detect environmental stresses such as drought, salinity, heat, and cold.[89] While Yin and Dong[90] showed changes in bioelectric potential in maize under water and light stresses, bioelectric signals alone cannot identify the specific cause of stress. Integrating data from multiple sensors along with machine learning and data modeling may improve accuracy and interpretation.

2.3. Multimodal Sensors. Simultaneous monitoring of a large number of related signals on the same plant can provide unique insights into how plants cope with stressful events.[91] Multimodal WPS sense several different signals derived from the plant or its immediate surroundings, making them better tools than sensors, which only track one signal. Many multimodal WPS have been developed, and these can broadly

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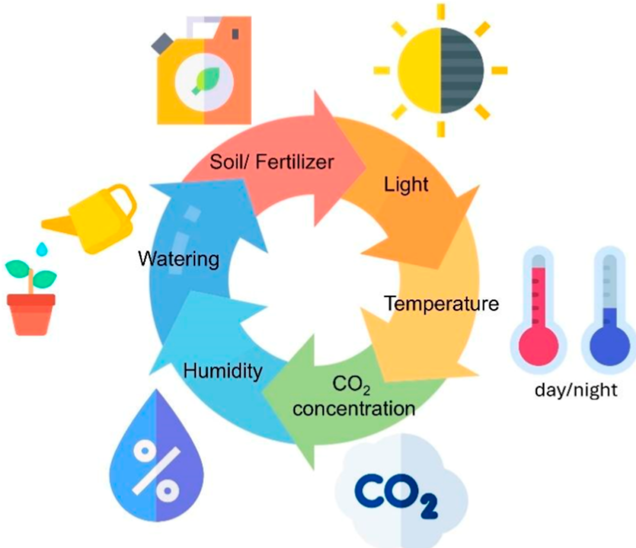
Table 2. Guide for Adequate WPS Testing and Reporting of Obtained Results: Environmental Factors to Consider When Growing Plants and Conducting Measurements with WPS on Plants[a]



Ecophysiological Considerations
Plants show biological variation, so measuring a signal on one plant only is insufficient. Also, plants respond to changes in their environment, which can greatly affect the signal. Additionally, internal rhythms, such as the circadian clock, can affect the measured signal.[137] Plant-to-plant and spatiotemporal variation need to be considered when designing experiments.
Use and report common agricultural practices. Important environmental parameters and practices include watering, fertilizer application, light intensity, photoperiod, day and night temperature, CO_2 concentration, and air humidity. When growing plants indoors, these factors should be managed, recorded, and reported in the manuscript describing the WPS. When growing plants outdoors, many of these factors will be uncontrolled but should be recorded. See Poorter et al.[138] for more detailed instructions.
Use an appropriate number of biological replicates, but at least three per treatment. The sample size depends on signal variability and the expected size of the treatment effect. In figure captions, report the number of biological replicates.
When treating plants with a stressor, report on the dose (intensity x duration) whenever possible. For example, only mentioning the application of a UV-A treatment without dose[139] is insufficient, as UV-A is not generally detrimental to plant growth,[140] but unrealistically high UV-A dosages likely are.
Avoid legacy effects: Plants acclimate to their environment,[141] and their response to a future treatment will be influenced by their past. Thus, applying one experimental factor after another on the same plant is strongly advised against. Instead, apply different treatments to different plants that were grown in the same way.
Sensor Functioning
Confirm the reliability of sensor readings in vivo, using completely independent measurements with a different sensor (cross-validation). Examples of good practice include the following:
• Barbosa et al.[40] cross-validated a water loss sensor by monitoring the rate of weight loss of detached leaves on a scale.
• Diacci et al.[64] collected tree sap and used an enzymatic assay to measure xylem sap glucose concentrations to validate a sensor that could measure xylem glucose concentrations in vivo.
• Zhang et al.[142] developed a sap flow sensor that was tested on peduncles of fruits, and the rate of change in fruit mass was used as cross-validation for the rate of sap flow.
Make sure that the sensor is optimized and calibrated for the range of the system/species you want to measure in (e.g., Diacci et al.[64]).
Test whether sensor attachment to the plant has adverse effects on plant growth and physiology. If the sensor is invasive (e.g., microneedles), check whether wound responses by the plant affect sensor functioning.[44,64]
Test whether the sensor remains attached to the plant organ of choice under field conditions and in the long term.
Reporting
Show convincing images/videos of WPS on plants, instead of merely showing drawings or conceptual figures.
If sensors were tested in the open field or greenhouse, provide location coordinates. Provide relevant environmental conditions, possibly using data from a nearby weather station.
A good understanding of plant eco-physiology, including the use of appropriate terminology, is useful for appropriate reporting and interpretation of obtained results. Consult plant biology textbooks and papers relevant to the field of the sensor being tested, or ask an expert.
Because plants constantly respond to their environment, signals measured by a WPS on the plant can only be interpreted relative to the environmental conditions the plant was exposed to during the measurement. For example, showing the rate of leaf transpiration over time without reporting the dominant drivers of leaf transpiration (e.g., irradiance, air temperature, air humidity, air velocity) is next to meaningless.
Include relevant experimental metadata (e.g., genotype, growth conditions, and experimental conditions). See Table 2 in Poorter et al.[138] for an overview.
Use units relevant for plant biology. For example, when reporting on light intensity, use photosynthetic photon flux density (PPFD; unit: μmol m^{-2} s^{-1}).

[a]Each icon in the graphic was sourced from Freepik (https://www.freepik.com/).

be categorized into two groups: those focused on environmental signals as well as a measure of growth[11,12,92−95] and those incorporating environmental signals with plant physiology, including electrochemical sensors of water and nutrient levels;[56] SA, ethylene, VPD, radial stem growth, temperature, and RH;[19] VOCs, temperature, and RH;[96] and relative water content, surface temperature, and bioelectric potential.[90]

3. APPROPRIATE TESTING OF WPSs ON PLANTS

Developers of WPSs should show how well these can be "worn" by plants and whether the signals they measure are reliable and relevant. This is crucial for the application of WPS in practice. However, in many experimental WPS studies, actual testing of WPSs on plants was treated like an afterthought: while lots of time and effort were invested in

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developing the sensors—including detailed descriptions of sensor design, working principle, and fabrication, as well as laboratory testing of basic physical and chemical properties—plants and their interaction with the sensors were often barely considered (though see ref 97). We surveyed the literature to obtain a more objective picture of how well sensors were tested on plants, assessing 93 experimental studies published between 2014 and 2025 (Table S1). In all studies, sensors were tested on intact plant material (either complete plants or detached plant organs). However, in many cases, this was done haphazardly. Below, we list the most commonly encountered problems.

First, we found that the environmental conditions that influence plant growth and physiology were often not adequately (or not at all) reported; this was the case in ~88% of all studies, many of which (~46% of studies) hardly provided any information on the plant material used in their materials and methods sections (Figure 3). This lack of proper reporting of environmental conditions during plant cultivation and/or during testing of WPS on plants suggests an alarming lack of awareness that plants are complex organisms that respond to their environment, in both the short and the longer term (see Table 2). Plant-environment interactions affect most signals measured on plants, which is crucial for interpreting sensor information derived from plants.

Second, we found that in approximately 73% of all studies, the sensor was tested on one plant only (i.e., $n = 1$), or it was not clearly reported how many biological replicates were used (Figure 3). Often, different treatments with only one biological replicate each were applied, or several treatments were applied in succession on the same individual;[62,96] the latter practice creates legacy effects that needlessly complicate data interpretation. These experimental practices are very problematic, as they ignore the effects of biological variation on the measured quantity and often make it impossible to draw conclusions as to the proper functioning of the sensor.

Third, in 68% of all cases, the data obtained by WPSs in vivo was not cross-validated by an independent measurement (Figure 3). Even though many sensors were cross-validated and calibrated in vitro (in the lab and when not attached to the plant), we argue that this is insufficient: it cannot be assumed that the calibration between phenomenon and signal will hold once the WPS is attached to the plant, as the signals generated by the plant are often noisier than those in vitro.

In a further 74% of studies, WPSs were attached to plants under lab or climate chamber conditions only, even though such conditions are clearly a very far departure from greenhouses or the open field. Testing in harsh and fluctuating environments is a must if authors claim their sensors contribute to precision agriculture (by which they presumably mean open field). Alternatively, authors would have to clearly state for which crop production environment the WPS is meant for.

Finally, approximately two-thirds of all studies (62%) contained either no treatment, meaning a sensor was attached to a plant in the environment the plant happened to be in, or the treatments applied were inadequate for testing whether the WPS was functioning correctly. For example, Chen et al.[61] developed an electrochemical sensor that could detect glucose concentrations; when testing the sensor on single tomato or *Aloe vera* plants in the lab, there was no attempt to correlate the measured signal (a nanocurrent) against glucose concentrations, nor did the authors compare signals measured in control vs stress treatments of any kind.[61] In such cases, it is completely unclear whether the produced signal is physiologically meaningful.

4. MULTIFACETED UNDERSTANDING: WPS DEVELOPMENT AND APPLICATIONS

To achieve actionable insights for plant health monitoring through WPSs, a multifaceted understanding of several factors is required, including (1) relevant temporal scales for stress detection and (2) mitigation of interferences of WPSs on plant physiology.

4.1. Temporal Scale of Stress Detection. One fundamental question in plant stress monitoring is how quickly a signal related to stress can be measured. Unfortunately, very few papers on WPSs exist that have adequately tested numerous plant species and environmental conditions to determine the precise temporal scales for identifying plant abiotic and biotic stress.

Regarding abiotic stress, studies reveal varied response times depending on the stressor. Yang et al.[95] observed growth changes in *Brassica rapa* leaves exposed to heat and drought stress within 2 days, with sensors operating over a six-day period. Lee et al.[96] found that LSH changes in tomato (*Solanum lycopersicum*) indicated drought stress after at least 5 days, while salinity stress was detectable within 1 day. Salt stress induced changes in IAA levels in soybean (*Glycine max* (L.) Merr.) within 36 h,[74] while two other studies observed changes in SA levels under salt and drought stress within 4 days.[19,73] In bell pepper (*Capsicum annum* L.), water stress caused SA and ethylene to increase within 1 day (with VPD levels showing slower changes), whereas in a separate experiment in cabbage, changes in SA and ethylene took 5 days.[19] Utilizing LSH or VPD measurements over a minimum of 5 days may be essential for reliable drought detection, whereas salinity stress may be identified much faster. Notably, the integration of phytohormone measurements, such as SA and ethylene, indicates that these responses can occur rapidly within 1−5 days. Sensor deployment and data analysis should be tailored to the stress of interest.

For biotic stress, responses are also manifest within a few days. After fungal infection, increased SA levels were detected within 4 days in tobacco leaves (*Nicotiana tabacum*).[9,73] Similarly, increased VOC levels were detected within 4 days postinoculation upon tomato late blight infection caused by *P. infestans*[85] or the tomato spotted wilt virus.[96] These studies indicated that using a combination of leaf humidity and/or VPD, phytohormones, and/or VOCs might provide a means for stress detection, including both abiotic and biotic stress. However, further research is needed to understand these temporal scales and validate them across a broader range of plant species, pathogens, and environmental contexts.

4.2. WPS Interference with Measurement. The physical presence of a sensor has the potential to perturb air (affecting stomatal function on the abaxial leaf surface), light availability, and water-nutrient exchange at biointerfaces. For instance, if gas diffusion is impeded by a sensor, the measured signal—regardless of its nature—could be affected, potentially introducing artifacts. However, interference in WPSs can be more complex than we might initially consider, spanning from physical design, material interactions, environmental fluctuations, and the sensor's inherent operational characteristics. Physical design elements, such as cable attachments for the power supply and/or data transmission, can affect plant

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movement, light, and airflow. The size and position of sensors also lead to localized changes in the environment that impact plant behavior. Second, environmental factors can modify the sensors influence. For example, strong sunshine during the day may increase heating caused by the sensor, leading to changes in the plant's responses. Third, material interactions, such as chemical leaching and surface interactions between the sensor and plant (which can physically affect gas exchange, water retention, or microbial activity), also contribute. Regarding the sensor's inherent operational characteristics, strain sensors, for example, can affect plant cells and differentiation through the application of strain and pressure. Similarly, sap flow heat thermal methods, such as the heat pulse[43] and the heat dissipation method,[44] may alter plant physiology due to the repeated application of heat pulses. Thorough testing that leads to an understanding and mitigation of these interactions is required. Such testing could come in the form of comparisons of plant growth and physiological parameters such as photosynthetic activity, transpiration, and growth, with and without sensors under the same environmental conditions. Furthermore, authors should consider minimizing interferences, such as reducing bulky cables for battery and data transmission and using wireless sensors (e.g., ref 56).

5. WPS APPLICATIONS IN DIFFERENT PRODUCTION ENVIRONMENTS

WPS offer advantages over traditional precision agriculture tools such as drones, satellites, and soil-based probes: unlike these indirect methods, WPS collect data from the plant's immediate environment, which allows for more accurate and localized monitoring. However, sensors initially developed in the lab need to be thoroughly tested in the environments for which they are intended; aspects include durability, reliability, and accuracy.[98]

Developers of WPSs should be aware that there is a range of crop production systems that differ in roughness and controllability of the environment, as well as crop resource use efficiency—these are exemplified here as open-field agriculture, greenhouses, and vertical farming systems (VFSs) (Figure 4).[99,100] These differences between agricultural systems pose a number of challenges and opportunities for the WPS design and use cases, as discussed below.

5.1. Open-Field Agriculture. In the open field, WPS must endure a harsh and highly variable environment, including direct sunlight, UV radiation, rain, wind, dust, and temperature fluctuations. Sensor durability under such conditions is a critical constraint, as degradation due to UV radiation, water entry, and mechanical stress from frost and wind can severely impact sensor longevity and performance.[101] Robust encapsulation,[43] flexible mounting techniques, adhesive backing layers, and stretchable sensor designs help maintain sensor attachment to plants during mechanical disturbances.[102−104]

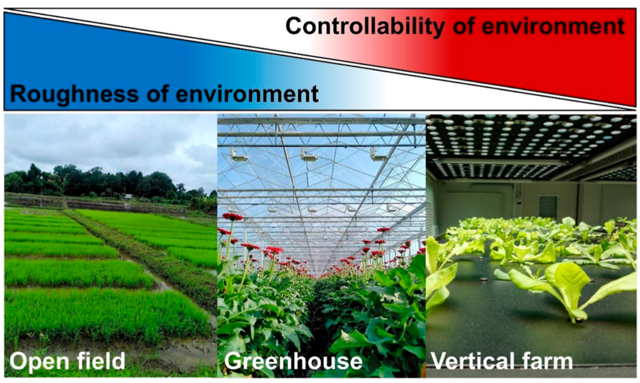

Figure 4. Various crop production systems (open field, greenhouse, and vertical farm) offer gradients of environmental roughness and controllability that pose unique challenges and opportunities for WPSs. All images © Elias Kaiser.

Apart from physical durability, large temperature variations can cause baseline drift or measurement inaccuracies, especially in impedimetric and fiber optic sensors.[40] T_{leaf} can differ substantially (by up to 18 °C) from ambient air temperature due to sunlight and transpiration and additionally can fluctuate very rapidly.[105] WPS typically require thermal compensation, robust protective packaging, or careful shielding and calibration to ensure accurate and reliable performance under extreme temperatures.[106] Furthermore, natural variability in soil moisture, nutrient availability, and local microclimates makes data interpretation challenging: sensors on individual plants may detect stress signals, such as elevated T_{leaf} or altered electrical responses, that neighboring plants do not exhibit. Precise sensor placement and local calibration are essential to accurately interpret sensor data and capture representative environmental conditions.[19,107]

Supplying continuous power to the WPS in the field is challenging, and potential solutions include low-power electronics, battery-efficient communication protocols, and renewable energy harvesting. Small photovoltaic (PV) cells can recharge batteries during the day to enable continuous and long-term monitoring.[108] Also, piezoelectric and triboelectric generators can convert mechanical energy from, e.g., wind or raindrops into electricity.[56]

Reliable wireless communication is another challenge;[109] wireless solutions include Bluetooth Low Energy (short-range), Zigbee (mesh networking), and LoRa (long-range, low-bandwidth). LoRa is particularly effective outdoors, transmitting sensor data over >1 km, while mesh networking helps sensors route data around obstacles.[110] Although outdoor environments show low signal interference, this can still occur, making low-power, narrow-band protocols ideal for WPSs that transmit minimal data.[111] Field deployments often use solar-powered gateways to collect and upload sensor data to cloud platforms, using buffering or intermittent transmission to ensure data consistency despite connectivity interruptions.[112]

An attractive use case of WPSs in the field is the detection of abiotic stresses (nutrient deficiency, drought), infections, or infestations, which, if done early enough, may help contain them. Future integrated systems, in which WPSs are in wireless communication with drones and field robots, may enable autonomous systems that tackle a range of stresses early on.[29] Early warnings, especially in the case of diseases, may prevent crop losses and optimize the number of pesticide applications. Also, WPSs could provide feedback on the efficacy of pesticide applications by monitoring plant stress responses postapplication. While this would be highly beneficial, current WPS publications related to pesticides do not track pesticide degradation in field conditions. For example, the United States Environmental Protection Agency provides guidelines and regulations regarding worker protection safety restricted-entry intervals (REIs), i.e., the periods of time to stay away from the site where pesticides are applied; these range from 12 h to several days.[113] Using WPSs in the field to track pesticide

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residuals and thus optimize REIs is an attractive use case of WPSs.

5.2. Greenhouses. Greenhouses cover at least 1.3 million hectares worldwide; this number has grown tremendously in recent years, especially due to rapid greenhouse area growth in China.[114] In greenhouses, natural sunlight is sometimes supplemented by artificial lighting, and environmental variability is reduced compared to that in the open field, protecting crops from most extremes. While there is less variation in temperature and humidity, and sensors are not directly exposed to wind and rainfall, WPSs have to cope with high humidity (sometimes leading to condensation), sunlight (but not UV radiation, which is typically filtered out by greenhouse cover materials), and high temperatures.[115] WPSs in greenhouses often use wireless communication technologies similar to those used in the open field.[29,116]

Several examples of successful sensor testing in greenhouses exist: integrated flexible strain sensors, e.g., mounted on fruits or the stems of tomato plants, showed robust and reliable performance in the greenhouse.[117] Biocompatible impedimetric sensors accurately measured dynamic changes in leaf water content of soybean in greenhouses.[40] In addition, flexible plant sensors attached directly to leaf surfaces provided accurate, real-time monitoring of dynamic changes in RH and temperature at the leaf level, allowing for monitoring of VPD. Using this information, growers can optimize temperature and humidity settings, water and nutrient efficiency, and disease control.[118]

In the controlled but dynamic greenhouse environment, WPSs could support precise monitoring, environmental adjustments, and systematic crop management.[92,112] Especially in high-tech greenhouses, integration of WPSs into the greenhouse management system could establish dynamic feedback mechanisms between plants and their environment, enabling fine control of climate set points. Furthermore, while recent years have seen promising developments toward fully autonomous greenhouses,[99,119,120] the availability of cheap, precise, and compact sensors capable of transducing signals from the plants—such as WPSs—is still a bottleneck.[6]

5.3. Vertical Farming Systems (VFSs). Vertical farms offer unique conditions for WPSs. These facilities typically rely on stacked layers of hydroponic or aeroponic systems, along with LED lighting that provides illumination for year-round production.[108,121,122] Although the absence of external weather conditions simplifies sensor durability, LED lighting used for plant growth can introduce interference and signal noise into optical sensor measurements. As a result, sensors can require synchronization with lighting cycles, optical filtering, or in situ calibration.[98]

Although VFSs enable very high productivity,[123] they are extremely energy-intensive, and electricity costs make up 20−40% of production costs.[124,125] Increasing energy use efficiency as well as costs per unit of electricity used is thus paramount, and both could be achieved by smart, integrated crop monitoring and modeling systems that enable dynamic climate control inside the VFS.[121] VFSs could integrate WPS data directly into machine learning algorithms or digital twin models that predict plant growth trajectories and resource requirements in real time. This would allow growers to adjust nutrient recipes and lighting schedules based on real-time plant feedback, thereby optimizing crop cycles and reducing operating costs.

In all production systems, sensors and their electronic components may be exposed to water droplets (condensation) and thus require waterproof or water-resistant encapsulation materials that allow for effective measurements over long periods of time.[37] This requirement is driving research into advanced packaging techniques that can protect sensors from moisture without reducing their sensitivity.[126]

Due to their high sensitivity and lightweight construction, it may be that not all WPSs are actually rugged enough for the open field. In other words, there may be a trade-off between ruggedness and sensor functionality. However, as we highlight in this section, this does not necessarily have to be a problem; such sensors could still be very valuable in crop monitoring in controlled environment agriculture (greenhouses and VFSs).

6. CONCLUSIONS

Wearable plant sensors (WPSs) have tremendous potential to revolutionize crop monitoring and could thus provide real benefits at a time when agriculture faces monumental challenges. The use of WPSs may help reduce crop losses, increase resource use efficiency, and automate crop production. However, for these benefits to materialize, WPSs need to be tested on crops more thoroughly and in all production environments for which they are intended. Such testing requires experiments that contain adequate treatments for the sensor at hand and are set up in a statistically reliable fashion. When designing new WPSs, developers should make conscious decisions regarding which production environment the new sensor is intended for; this will guide them in deciding what properties the sensor should have. Furthermore, for proper interpretation of the signals generated by WPSs, developers need to be aware of the plant−environment interactions driving variation in the signal and of biological variation in general. Another feature that should be explored in future WPSs is sensors that can measure several signals and, based on signal strength and kinetics, can differentiate between various biotic or abiotic stresses; machine learning may supercharge this approach. Although outside the scope of WPSs as defined in this review, other sensing approaches such as RGB imaging, hyperspectral imaging, Raman, and infrared sensing share similar goals of noninvasive, real-time monitoring. These technologies may serve as complementary tools that, when combined with WPSs, could further enhance plant phenotyping and crop monitoring in the future. Altogether, we propose that WPSs can be a very valuable addition to crop monitoring if their testing on plants is done properly.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssensors.5c02510.

> Details on the literature search for Tables S1 and S2, Figure 2, and Figure 3; flowchart for the implementation of proper testing of plant wearable sensors on plants; list of experimental studies reporting on WPSs; list of review papers reporting on WPSs; summary of nutrient-related studies discussed in this review; reported WPSs for phytohormones; and checklist for conducting realistic, reliable experiments with WPSs on plants (PDF)

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Notes

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VOCABULARY

Biological replicate: an independently grown and treated plant; a distinct biological unit that captures the natural variability among individuals, rather than just measurement or technical error

Crop monitoring: systematic observation, measurement, and assessment of crop growth, development, and condition over time in order to support management decisions and improve yield, quality, and sustainability

Crop production system: a set of practices, resources, and environmental conditions that are used to grow and manage crops for a specific purpose (e.g., food, feed, fiber, or fuel)

In vivo testing: study or measurement of physiological, biochemical, or molecular processes within living plants or plant organs, under natural or controlled conditions that preserve normal biological function

Plant-environment interactions: processes and responses through which plants perceive, respond to, and influence their physical, chemical, and biological environment, including factors such as light, temperature, water, nutrients, soil, and other organisms

Precision agriculture: management strategy that uses geospatial, sensor, and analytical technologies to observe, measure, and respond to variability in crops and their environment for higher productivity and sustainability

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