

RESEARCH ARTICLE

Growing Fiber Sensors Enable Continuous In Vivo Monitoring of Plant Hormones

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Received: 15 May 2026 | **Revised:** 14 August 2026 | **Accepted:** 24 August 2026

Keywords: growing sensor | in vivo monitoring | plant hormones | soft electronic conductor

ABSTRACT

Plant stress during growth, caused by extreme environments and biotic attacks, threatens global biodiversity and crop production, necessitating urgent elucidation of plant adaptation mechanisms. Endogenous hormones of plant growth serve as master regulators and earliest indicators of stress adaptation, making it crucial to monitor their dynamics continuously. However, existing methods, including chromatography and electrochemical probes, fail because of their mismatch with the irreversible and plastic nature of plant growth. Here, we unexpectedly find a growing fiber sensor based on an electrode consisting of a dynamic polymer network infiltrated with liquid metal, termed metalgel. The sensor undergoes irreversible elongation ~up to 10 times its original length under just 3.2 kPa tensile stress, at least 2 orders of magnitude lower than existing electronic conductive systems, thus achieving synchronous deformation with plant growth without inducing mechanical damage or hormonal disturbances. Hormone dynamics and relevant signaling pathways during plant growth in response to pathogen infection, salt stress, and even extreme ultraviolet radiation are thus revealed by the sensor. This work provides quantitative insights into plant stress resilience mechanisms and offers a feasible route to alleviate the food and ecological crises.

1 | Introduction

Plants are essential for sustaining biodiversity [1, 2], feeding a global population of 8 billion people [3], and enabling human habitation beyond Earth [4]. Yet extreme environmental changes could threaten 70%–80% of plant species by the century's end [5–7]. Plant endogenous hormones are crucial messengers that regulate physiological processes in response to environmental

stress [1, 8, 9], and understanding the changes in hormones is key to grasping plant survival [10, 11]. Monitoring these hormones continuously would reveal the earliest biochemical stress responses and generate unique “hormonal fingerprints” for different stressors [8, 12], such as pathogen infection, salt stress, and radiation exposure, thus enabling the development of targeted strategies for crop resilience and ecosystem conservation.

Kuangyi Zou and Jiacheng Wang contributed equally to this work.

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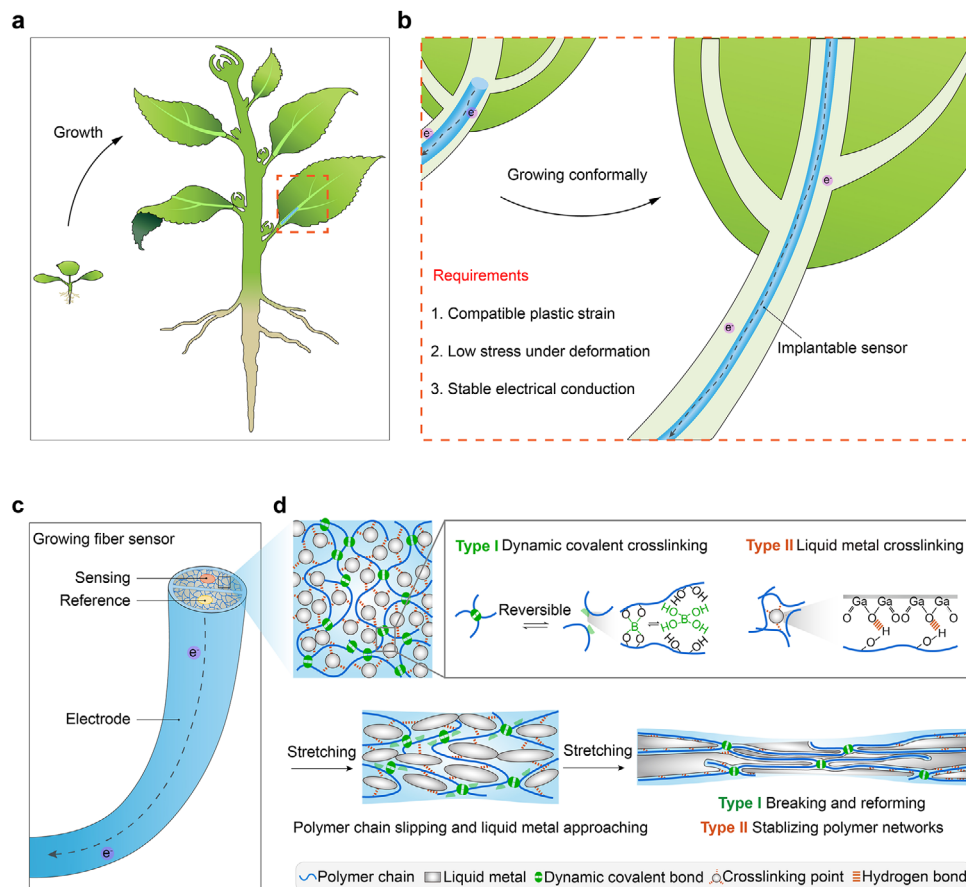


FIGURE 1 | Design of the growing fiber sensor for continuous plant endogenous hormone monitoring. (a) Schematic illustration of large and irreversible deformations that occur during plant growth. (b) Schematic illustration of the requirements for implantable sensors to achieve continuous and accurate monitoring during plant growth. (c) Schematic illustration of the growing fiber sensor. (d) Schematic illustration of the physical images of the electrode featuring liquid metal stabilizing dynamic covalent crosslinked polymer networks at its initial stage and stretched state.

However, it remains impossible to continuously monitor hormones in growing plants. Chromatographic analysis requires the destruction of tissue through the excision and grinding of leaves, failing to achieve continuous monitoring [13]. Surface-based wearable sensors cannot access internal hormonal signals [3, 14, 15]. Electrochemical probes cause mechanical damage due to stress concentration as plant tissues expand around rigid sensors, thus altering local hormone levels with invalid measurements [16, 17]. The fundamental challenge lies in the growth pattern of plants. As their cells progress from division to maximal expansion, plants undergo permanent, irreversible elongation by 3- to 10-times (Figure 1a) [18, 19]. Therefore, it is necessary to develop a sensor that matches the growth pattern of plants (Note S1).

Here, we present a fiber sensor that is made of metalgel with a dynamic polymer network and infiltrating liquid metal to achieve 1100% plastic elongation under just 3.2 kPa tensile stress, and it can thus be implanted into plants to deform synchronously and function effectively within growing tissues (Figure 1b, Note S1, and Figure S1), serving as an ideal monitoring system. First, it undergoes large, irreversible deformations to match plant elongation without elastic recovery or fracture. Second, it elongates under minimal tensile stress to avoid tissue damage and artificial hormone fluctuations. Third, it shows constant

resistance during growth to ensure that sensing signals reflect only chemical changes. The growing fiber sensor imposes minimal mechanical stress on tissues, enabling continuous hormone monitoring throughout the critical elongation phase. We further capture real-time hormone dynamics in response to pathogen infection, salt stress, and even extreme ultraviolet radiation, revealing how plants prioritize specific signaling pathways and exhibit distinct hormonal signatures under different stresses.

2 | Results and Discussion

2.1 | Design of the Growing Fiber Sensor

The fiber sensor comprises three main components: a liquid metal/polyvinyl alcohol (PVA) electrode core, a terminal sensing layer modified with molecularly imprinted polymers for specific hormone recognition, and an outer insulating layer (Figure 1c and Figure S2). The fiber geometry enables minimally invasive implantation into plant vascular tissues [20]. The fiber electrode employs liquid metal to stabilize dynamic PVA networks (Figure 1d). Liquid metal particles are uniformly distributed throughout the PVA polymer networks (Figure 2a). Fourier transform infrared (FTIR) spectroscopic analysis revealed the presence of two interaction modes in the liquid metal/PVA electrode

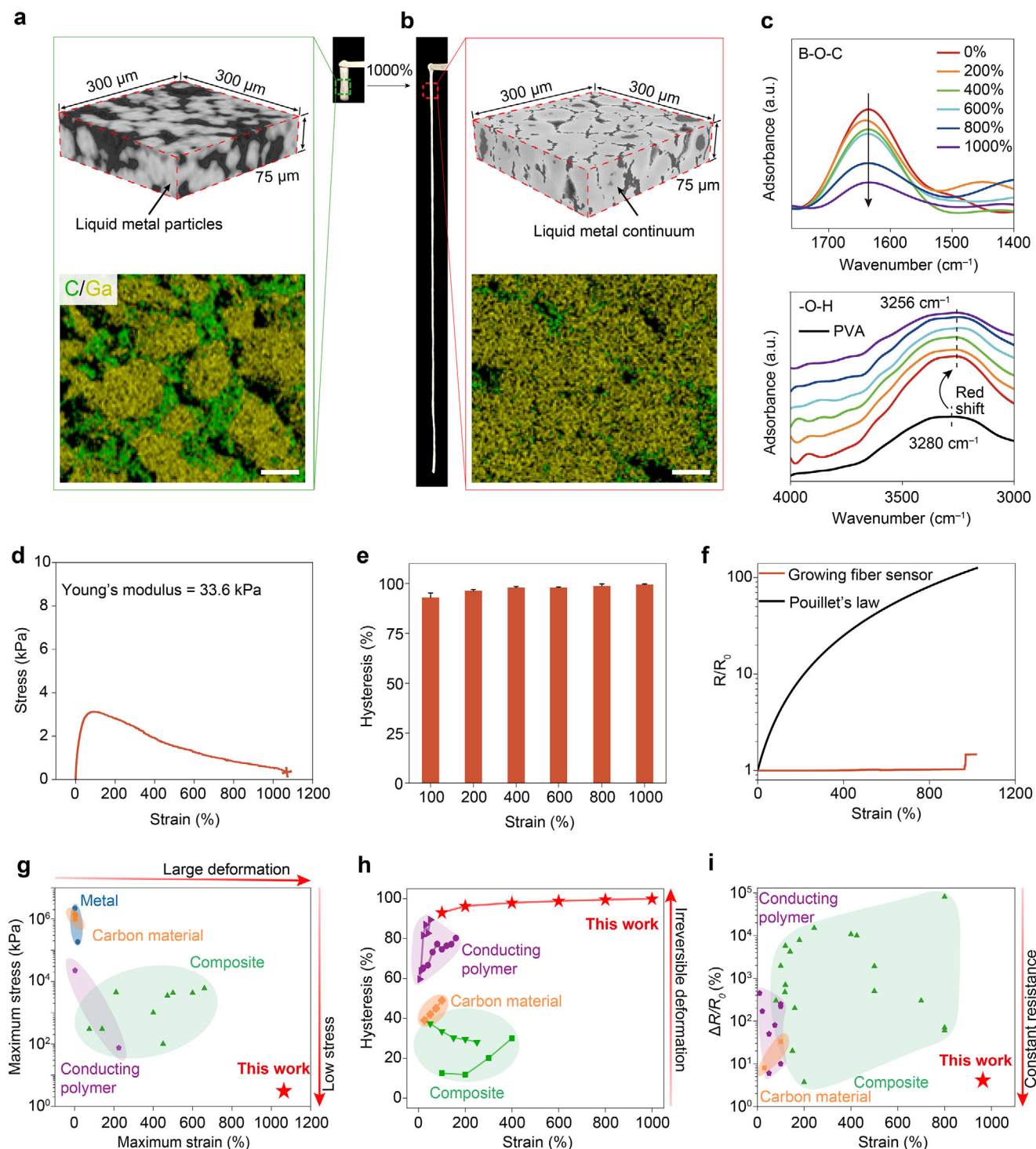


FIGURE 2 | Structure and performance of the growing fiber sensor. (a,b) Optical, energy-dispersive spectroscopy, and micro computed tomography images of the sensor in the pristine state (a) and after stretching to 1000% and unloading (b). Scale bar: 25 μm . (c) Fourier-transform infrared spectroscopy of the electrode at different stretching strains of 0%, 200%, 400%, 600%, 800%, and 1000% compared with dynamic covalent crosslinked PVA gel. (d) Stress-strain curve of the uniaxial stretching of the growing fiber sensor. (e) Statistics on the mechanical hysteresis of the sensor at different tensile strains. Values are shown as the mean $\pm$ SD for $n = 3$ samples. (f) The resistance changes of the sensor during uniaxial stretching until fracture. (g) Ashby-style plot comparing maximum strain and maximum stress of the growing fiber sensor to existing systems. Metal-based, carbon material-based, conducting polymer-based, and composite-based systems are shown in the blue, orange, gray, and green ranges, respectively. References and data are provided in Table S1. (h) Ashby-style plot comparing the strain and mechanical hysteresis of the growing fiber sensor to existing systems. Carbon material-based, conducting polymer-based, and composite-based systems are shown in the orange, grey, and green ranges, respectively. References and data are provided in Table S2. (i) Ashby-style plot comparing the strain and electrical stability ($\Delta R/R_0$ means relative resistance changes) of the growing fiber sensor to existing systems. Carbon material-based, conducting polymer-based, and composite-based systems are shown in the orange, gray, and green ranges, respectively. References and data are provided in Table S3.

(Figure 2c). The characteristic absorption peak of the B—O—C bond at 1630 cm^{-1} represents the dynamic covalent crosslinking [21, 22] of boronic ester bonds between polymer chains. Introducing liquid metal causes a red shift in the characteristic absorption peak of —OH from 3280 to 3256 cm^{-1} compared to pure PVA gel [23, 24], which represents the existence of hydrogen-bonding interactions between the polymer and the liquid metal particles.

The PVA networks have three main crosslinking modes: dynamic covalent crosslinking, physical crosslinking, and permanent covalent crosslinking [25]. To minimize stress during deformation, dynamic covalent crosslinking with the lowest bond energy was thus utilized to crosslink the polymer networks (Figure S3). However, the PVA network relying solely on dynamic covalent crosslinking displayed unstable liquid-like behavior and was prone to flow (Figure S4a), exhibiting a loss modulus (G'') greater than the storage modulus (G') (Figure S4b) and $\tan \delta > 1$ across the strain sweep range (Figure S4c), indicating sol-like behavior. However, with the addition of liquid metal particles, the gel system became stable and resistant to flow (Figure S4d), resulting in a rheological transition to $G' > G''$ (Figure S4e) and showing a transition from $\tan \delta < 1$ to $\tan \delta > 1$ with increasing strain (Figure S4f), characteristic of gel-like behavior. Consequently, the liquid metal not only acts as a conductive phase in the PVA networks but also as a second interaction that significantly enhances the stability of the originally liquid-like, dynamic covalent crosslinked PVA networks.

Figure 2b shows the fiber electrode stretched to a large strain of 1000%, retaining the deformed state after unloading with almost no elastic recovery. During stretching, the liquid metal particles were observed to gradually coalesce, ultimately forming a liquid metal continuum throughout the polymer network. We also characterized the fiber electrode under stretching by FTIR (Figure 2c). These results show that the peak intensity of the dynamic boronic ester bond gradually decreases with increasing strain, indicating the breaking of dynamic covalent bonds induced by stretching. Meanwhile, the characteristic absorption peak of the —OH bond, the second interaction mode of the electrode, shows no additional observable peak shift during stretching. These results reveal the underlying mechanism: dynamic covalent bonds broke and reformed preferentially under stretching, allowing PVA chains to slide. This chain slippage, in turn, drove the progressive coalescence of the liquid metal. Throughout this process, hydrogen bonds served as stable anchors, preserving the structural integrity of the fiber sensor (Figure 1d).

2.2 | Mechanical and Electrical Properties of the Growing Fiber Sensor

The stress-strain curve of the fiber sensor exhibits a maximum strain of 1100% with a maximum stress of only 3.2 kPa and a Young's modulus of 33.6 kPa (Figure 2d), indicating that it can be deformed easily under minimal mechanical load. This performance originates from the rational design of the energy dissipation mechanism of the sensor, that is, dynamic covalent bonds with ultralow bond energy continuously break and reform as the strain increases. Replacing the dynamic covalent crosslinking with other crosslinking modes with higher bond energy (e.g., physical or permanent covalent crosslinking) resulted in samples

with significantly increased maximum stress of 29.3 and 51.7 kPa (Figure S5a,b), failing to meet the application requirements. To contextualize these properties, comparisons were made with sensing platforms using different electrode materials, including metal-, carbon-, conducting polymer-, and composite-based systems (Figure 2g). The maximum stress during stretching of the growing fiber was 5 orders of magnitude lower than that of metal- and carbon-material-based systems. Compared to conducting polymer-based and composite-based systems, it also showed a significant decrease of at least 2 orders of magnitude.

Plasticity, as quantified by hysteresis and irreversible deformation, represents another critical performance metric for the sensor, given the continuous and irreversible nature of plant growth. In stretching-releasing tests at strains ranging from 100% to 1000%, the sensor exhibited hysteresis values of 93.0%, 97.9%, 98.8%, and 99.5%, with corresponding irreversible deformations of 73.7%, 368.4%, 787.1%, and 988.2% at 100%, 400%, 800%, and 1000% strain, respectively, confirming its near-ideal plastic behavior with negligible elastic recovery (Figure 2e and Figure S6). This plastic character could enable the sensor to reduce damage to the growing plant tissues without exerting restorative stress.

Existing electronically conductive materials struggle to achieve both high plasticity and strain (Figure 2h). Intrinsically conducting polymers exhibit relatively high mechanical hysteresis (60%–89%) through rigid conjugated polymer chains sliding, but stretchability is restricted to 50%–160% due to a non-constructible polymer network structure. Carbon-based materials with engineered architectures and conductive composites exhibit higher strain (250%–400%), yet their high elasticity, dominated by energy-storing entropic mechanisms, leads to low hysteresis (30%–49%). In contrast, the fiber sensor exhibited unique energy dissipation. In the process of dynamic covalent bonds breaking and reforming, PVA chains underwent permanent and continuous slippage while being stabilized by liquid metal, contributing to the resultant large plastic strain.

Finally, we evaluated the electromechanical coupling performance of the sensor to assess potential signal interference during deformation. The sensor, with an initial conductivity of $6.79 \times 10^3\text{ S/m}$, exhibited minimal resistance variations under stretching, which were much lower than the values predicted by Pouillet's law. At nearly 1000% strain, the relative resistance change ($\Delta R/R_0$) was only 4% (Figure 2f), ensuring stable sensing signals throughout deformation. This was due to the progressive convergence and coalescence of liquid metal particles, which was promoted by the continuous slipping of polymer chains under stretching (Figure 2b and Figure S7), ultimately establishing a continuous conductive pathway throughout the polymer network. As a result, the electrical conductivity of the fiber electrode increased with increasing strain, effectively compensating for the geometric resistance rise caused by dimensional changes and thus maintaining a stable overall resistance (Note S2 and Figure S8). Existing electronically conductive systems struggle to continuously construct new conductive pathways to compensate for the resistance changes under large deformation due to the inability of conductive pathways to deform synchronously with the polymer network (Figure 2i). Therefore, they exhibited greatly increased $\Delta R/R_0$ from 3.7% to 10 700% as the strain increased from 10% to 800%. This growing fiber sensor achieved large plastic

deformation under ultra-low stress while maintaining nearly constant electrical resistance during deformation, satisfying all three core requirements for continuous hormone monitoring during plant growth.

2.3 | Continuous and Accurate Monitoring of Hormones During Plant Growth

We then implanted the fiber sensor into the leaf veins of the model plant *Nicotiana benthamiana*, with an electrochemical metal probe for comparison. The metal probe was unable to deform conformally with the plant's growth, which generated persistent mechanical stress at the sensor-tissue interface. This prolonged stress led to cellular damage and localized production of interfering hormones in the long term, resulting in inaccurate monitoring (Figure 3a,b). Consistent with this, after implanting the metal probe for 30 days, cross-section analysis revealed pronounced browning at the implantation site, indicative of phenolic oxidation resulting from cell rupture (Figure 3c). Trypan blue staining and TUNEL staining also confirmed extensive cell death in the adjacent tissues (Figure 3c and Figures S9 and S10). At the molecular level, the concentrations of abscisic acid, salicylic acid, and reactive oxygen species (ROS) at the implantation site were significantly higher than those in the remaining blades, indicating the existence of interfering phytohormone expression at the implantation sites caused by persistent mechanical stress (Figure S11).

In sharp contrast, the sensor grew conformally with the leaves without imposing appreciable mechanical stress. This was due to its ability to undergo large plastic deformation under minimal plant growth forces (Figure 3d). After implantation for 30 days, the sensor was observed to have grown with the leaves by approximately 100%, with its cross-sectional area ratio to the vein decreasing from 6.08% to 2.42% (Figure 3e and Figure S12). It showed no significant difference in growth rate compared to the device-free control group (Figure S13). There was also no significant difference in the tissue morphology of the implantation site compared with the device-free control group, confirming its successful bio-integration through conformal growth (Figure 3f and Figures S14 and S15). As a result, the sensor did not cause abnormal accumulation of ROS or mechanical stress-related hormones at the implantation site (Figure S11), thereby maintaining local molecular homeostasis. The sensor was thus shown to be biocompatible without causing disruption to the plant's normal physiology (Note S3 and Figures S16 and S17).

The ability of conformal growth with plants made the sensor capable of maintaining stable interfacial contact with the surrounding tissues under complex environmental conditions during plant growth. The sensor exhibited stable sensing performance with signal fluctuations less than 4.6% under the simulated wind and rain environments (Figure 3h, Note S4, and Figures S18–S26). In contrast, the probe lost effective contact with the tissues due to stress concentration under dynamic interference, and the sensing signal was attenuated by 90% (Figure 3g). Plant growth rates and extents vary significantly across developmental stages. To make the sensor widely applicable to various plants, we tested its sensing performance under different stretching rates (0.01–10 mm min^{−1}) and strains (100–1000%). Owing to the

stable internal resistance of the sensor during deformation, the sensor showed stable analytical performance across all strain levels (Figure S27), and the sensing signal exhibited minimal fluctuation of less than 5.8% compared to the static state across different deformation amplitudes and speeds (Figure 3i and Figures S28–S30).

Throughout the 30-day implantation period, the fiber sensor was capable of consistently monitoring hormonal signals (Figure 3j and Figure S31a). Furthermore, the sensor's readings consistently correlated with data from standard liquid chromatography-mass spectrometry (LC-MS) methods. Linear fitting curves maintained a coefficient of determination (R^2) above 0.96 at both the beginning and the end of the implantation period, demonstrating their accuracy in long-term monitoring during plant growth (Figure 3k,l and Figure S31b,c). This performance stemmed from the following key factors: (1) the sensor formed a compatible interface with plant tissues during plant growth, thereby minimizing the induction of disruptive hormones; (2) it maintained stable electrical conduction during deformation, keeping the sensing signals reliable under continuous growth.

2.4 | Decoding Plant Stress Responses via Continuous Hormone Monitoring

The growth and survival of plants have been persistently challenged by environmental extremes and biotic attacks. Among these, pathogen infection represents a quintessential and acute threat, characterized by its unpredictable onset and capacity for rapid systemic dissemination [26, 27]. The plant immune system's evolution is in a relentless arms race with pathogens, a battle played out over millions of years [28, 29]. The initial 24 h post-infection constitute a decisive phase where hormone (like salicylic acid) dynamics determine the fate of the interaction—immunity or disease [8]. By continuous monitoring of defense-related phytohormones, the logic of plant immunity would be truly deciphered, thus improving plant resilience in response to external challenges.

To evaluate the ability of the growing fiber sensor to be applied in continuous stress monitoring, we constructed biotic stress represented by *Phytophthora capsicum* infection and implanted the fiber sensor into the plant leaf vein (Figure S32). Upon infection, the sensor recorded a significant rise in salicylic acid concentration after 10 h, reaching 12.3 times the original by 24 h and continuing to increase in the absence of intervention. In contrast, the concentration of salicylic acid in the group without pathogen infection remained at a low level throughout (Figure 3m). This early hormonal surge correlated directly with a large-scale closure of leaf stomata, a critical physiological defense to block pathogen entry through stomata. (Figure 3n and Figure S33a,b) [30]. The sensor's electrochemical signal also reflected specific signaling pathways activated under pathogen stress. We performed time-course gene expression analysis at 0, 6, 12, and 24 h post-pathogen inoculation, during which the sensor recorded a sustained increase in salicylic acid concentration. The expression of key salicylic acid pathway genes, including *Isochorismate Synthase 1* for salicylic acid biosynthesis, *WRKY DNA-Binding Protein 40* for early salicylic acid-responsive transcription, and *Pathogenesis-Related Protein 1B* for systemic acquired resistance,

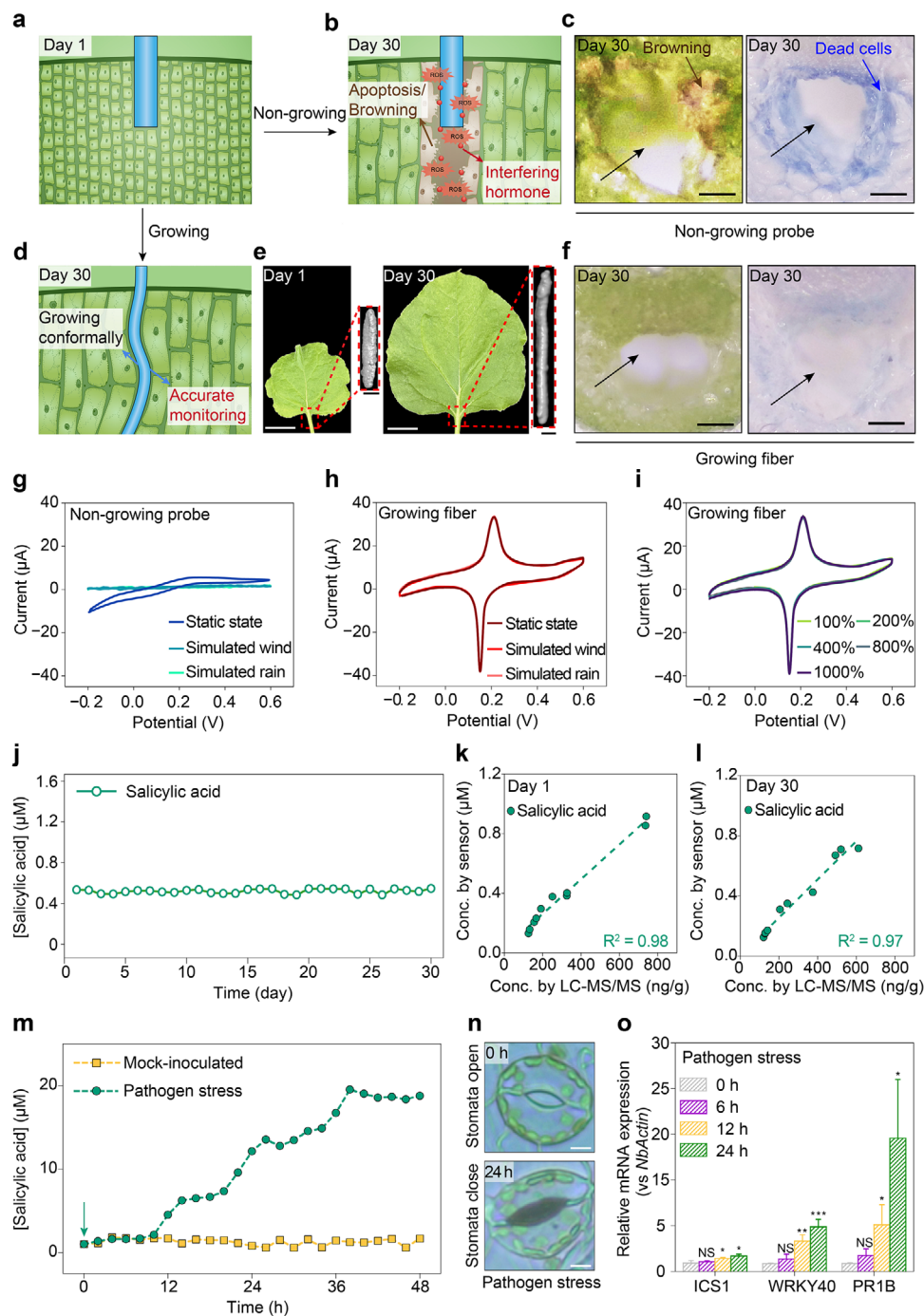


FIGURE 3 | Biocompatibility and electrochemical sensing properties of the growing fiber sensor. (a) Schematic illustrations of the sensor at the initial implantation. (b) Schematic illustrations of the non-growing fiber probe after 30-day implantation. (c) Optical microscope images of the cross-section of the veins at the non-growing probe implantation site (left) and the corresponding images after trypan blue staining (right). Scale bar: 400 μm . (d) Schematic illustration of the growing fiber sensor implanted in the plant tissue for 30 days. (e) Optical images of the leaves implanted with the growing fiber sensor on day 1 (left) and day 30 (right). Scale bar: 1 cm. Inset: Micro-CT images of the sensor in the veins. Scale bar: 500 μm . (f) Optical microscope images of the cross-section of the veins at the growing fiber sensor implantation site (left) and after trypan blue staining (right). Scale bar: 400 μm . (g), (h) Cyclic voltammetry of the non-growing probe (g) and growing fiber sensors (h) in static, simulated windy, and rainy environments (abscisic acid, 400 μM). (i) Cyclic voltammetry curves of the growing fiber sensor under different uniaxial tensile strains (abscisic acid, 400 μM). (j) The signal acquired by the growing fiber sensors in long-term monitoring of salicylic acid. (k, l) Linear fitting of the salicylic acid concentration monitored by the sensor on the same blade with that detected by LC-MS/MS on day 1 (k) and day 30 (l). $n = 10$. (m) Real-time changes in salicylic acid concentration under pathogen stress recorded by the growing fiber sensor (green arrow: the stress began). (n) Representative microscopic images of stomata at 0 and 24 h under pathogen stress. Scale bar: 5 μm . (o) Relative mRNA expression of Isochorismate Synthase 1 (ICS1), WRKY DNA-binding protein 40 (WRKY40), and Pathogenesis-Related protein 1B (PR1B) at 0, 6, 12, and 24 h under pathogen stress. Values are the mean $\pm$ SD for $n = 3$. p -value is calculated using one-way ANOVA. * $p \leq 0.05$, ** $p \leq 0.01$, and *** $p \leq 0.001$.

showed a corresponding upregulation that closely paralleled the sensor signal over time (Figure 3o). This combination of continuous hormonal data, physiological response, and gene expression validation formed a complete chain of evidence, demonstrating the sensor's ability not only to detect stress early but also to faithfully report the underlying signaling cascade. The sensor, with an unprecedented temporal resolution for capturing hormonal dynamics, demonstrates its ability to uncover plant stress response mechanisms, guide the development of targeted protection strategies, and ultimately contribute to more resilient plant systems.

The sensing platform was readily extendable to monitoring other defense-related phytohormones. As a demonstration, we applied the sensor to a salt stress plant model (Figure S34), a common abiotic stress. The sensor promptly detected an increase in the abscisic acid concentration after salt stress for 2 h, reaching 11.8 times the original by 6 h, and then rose steadily (Figure S35a). As expected for abscisic acid-mediated adaptation, this hormonal signal was followed by large-scale stomatal closure to reduce water loss (Figures S33c,d and S35b) [31]. Similarly, time-course analysis of abscisic acid-responsive genes at 0, 2, 4, and 6 h post-salt treatment confirmed that their expression dynamics were consistent with the elevated sensor readings across the monitored period (Figure S35c). Together, these results demonstrated the growing fiber sensor as a robust and versatile platform in delivering continuous, accurate, and timely hormonal dynamics across diverse stress types.

2.5 | Revealing Hormone Dynamics Signatures Under Different Radiation Regimes

The success of future long-term space missions relies on bioregenerative life-supporting systems, where plants serve as an indispensable source of food and oxygen [4]. However, extreme extraterrestrial conditions, such as on the Moon and Mars, pose severe challenges to plant growth. For instance, the absence of Earth's atmospheric protection exposes plants to high levels of ultraviolet radiation (UV), particularly UVB and UVC bands that are rare or absent on Earth's surface (Figure 4a) [32]. To engineer resilient plants and optimize artificial growth conditions, a quantitative understanding of plant real-time responses to UV exposure is essential.

As a proof of concept, we established a simulated space ultraviolet radiation system with soybean as an experimental model (Figure 4c). The soybean plants were subjected to three distinct wavelengths of UV light (UVA, UVB, and UVC) for varying durations (Figure S36), employing the growing fiber sensor to monitor dynamic changes in salicylic acid levels.

The sensor captured differential salicylic acid responses under UV irradiation at different wavelengths, revealing differentiated plant defense strategies (Figure 4b,d). It showed that UVC triggered an acute salicylic acid surge with a rise rate $>0.79 \mu\text{mol}\cdot\text{h}^{-1}$ (Figure 4e,f), as a result of UVC functioning as a high-energy stress that caused direct DNA damage and severe cellular disruption (Figure S37d). The result indicated that the high-rise rate of salicylic acid could serve as a sensitive early-warning biomarker for high-energy radiation leaks. UVB elicited a more

moderate yet sustained salicylic acid increase between 24 and 88 h (Figure 4d), which was mediated by the *UV Resistance Locus 8* photoreceptor pathway (Figure S37b). It initiated a defense signaling pathway that stimulated salicylic acid biosynthesis, which was further evidenced by the upregulation of defense-related genes such as *Chalcone Synthase* (Figure S37c). UVA induced only a mild salicylic acid response, consistent with its role in photomorphogenesis via *Cryptochrome* receptors rather than severe stress (Figure S37a).

The sensor data also established critical quantitative relationships between radiation dose and plant outcome. Longer exposure increased peak salicylic acid levels, with UVC inducing the highest concentrations, followed by UVB, and then UVA (Figure 4g-i). Moreover, using the sensor monitoring, we identified a damage threshold: peak salicylic acid concentrations exceeding $\sim 6.6 \mu\text{M}$ correlated with irreversible leaf death, as observed in groups B3, C2, and C3 (Figure 4h,i). These results indicated that, for our experimental subjects, UVB acted as a double-edged sword. Although it bolstered plant defense, an excessive dose (group B3) resulted in non-recoverable damage. Conversely, the harm caused by UVC presented a window for remediation if identified and countered in a timely manner (group C1). Notably, these hormonal dynamics by the growing fiber sensor preceded visible symptoms, demonstrating the sensor's unparalleled timeliness and accuracy in reflecting internal plant status (Note S5 and Figures S38-S40).

These findings paved the way for sensor-informed space agriculture in the future. On the one hand, the decoded relationship between hormone signatures and molecular mechanisms by sensor monitoring would provide a quantitative basis for selecting and engineering plants with optimal UV resilience, a critical step toward developing robust crops for extra-terrestrial cultivation. On the other hand, artificial growth habitats with an intelligent UV management system could be achieved by continuous phytohormone monitoring, that is, utilizing UVA for photomorphogenesis, applying UVB within the safe window to boost defenses without harm, and providing instant alerts for UVC leaks.

3 | Conclusions

We have developed a fiber sensor that grows synchronously with plants, enabling unprecedented continuous hormone monitoring during growth. The sensor captures real-time hormone dynamics in response to pathogen infection, salt stress, and extreme ultraviolet radiation, with stable performance over 30 days of implantation and reliable quantification of hormones within their physiologically relevant ranges. Notably, the sensor accommodates large deformation with minimal signal variation, demonstrating its capacity to maintain analytical fidelity throughout plant development. This growing fiber sensor opens transformative possibilities for plant science. First, the sensing platform can be generalized to monitor a broader spectrum of endogenous signaling molecules by designing sensing layers to enable a multiplexed view of signal crosstalk across plant development and stress response, moving beyond single-marker detection to decode multiple signal couplings. Second, extending single-node measurement to multi-node spatio-temporal sensing

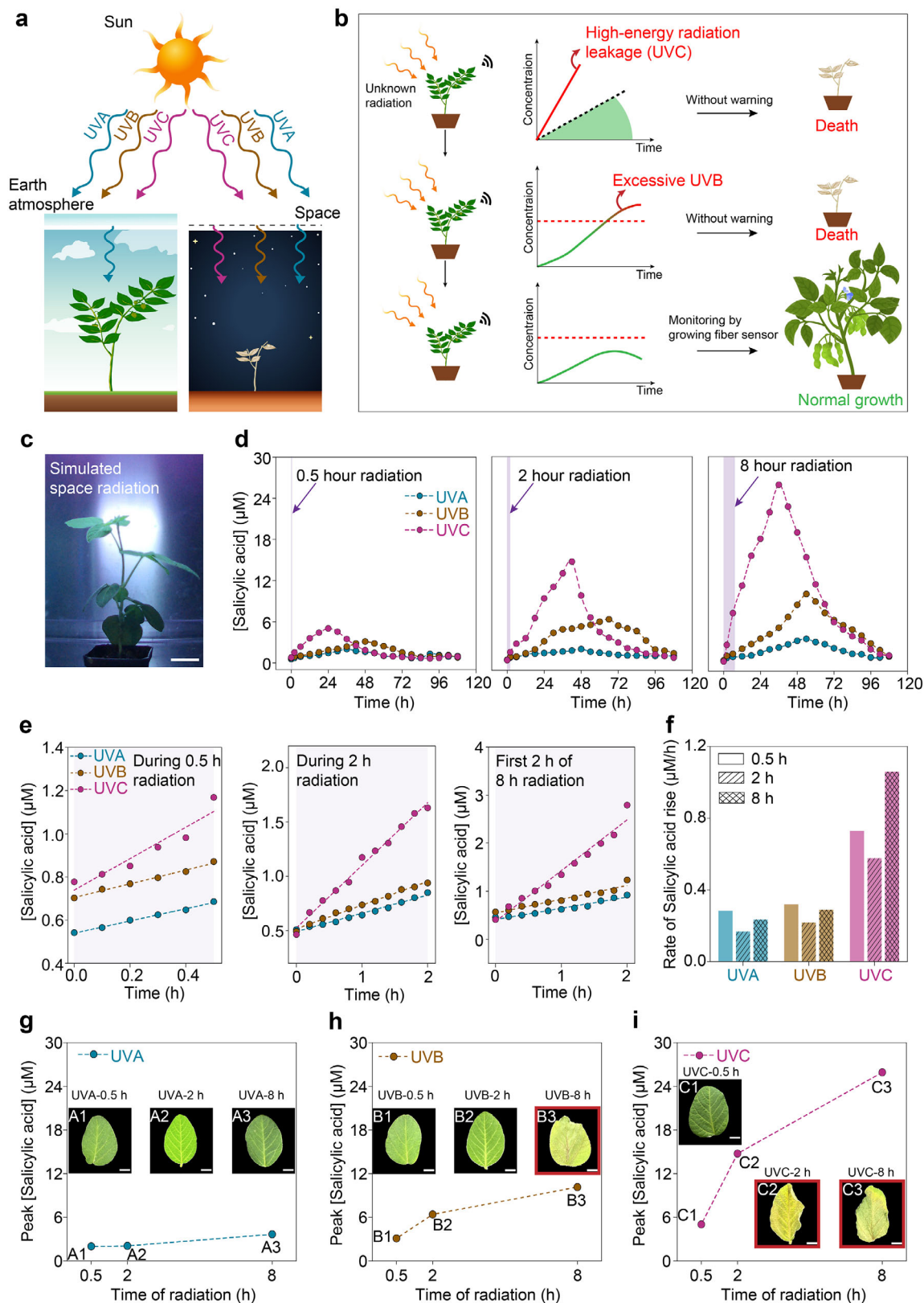


FIGURE 4 | Application in revealing hormone dynamics signatures under different radiation regimes. (a) Schematic illustration of ultraviolet radiation at the ground surface with and without an atmosphere, and its corresponding effects on plant growth. (b) Schematic illustration of the UV management for space farming by a growing fiber sensor. (c) Optical images of the simulated space radiation setup. Scale bar: 2.5 cm. (d) Real-time changes in salicylic acid concentration under different wavelengths of ultraviolet radiation for different durations recorded by the growing fiber sensor. (e) The rate of change in salicylic acid concentration under ultraviolet radiation of different wavelengths for different durations. (f) Statistics on the rate of change in salicylic acid. (g–i) The peak salicylic acid and related optical images of leaves at 108 h after exposure to UVA (g), UVB (h), and UVC (i) for different durations. The red border indicates the dead leaves. Scale bar: 5 mm.

networks could map biochemical gradients and signaling propagation, allowing researchers to resolve systemic signals from local perturbations, uncovering how different tissues orchestrate adaptive responses in real time. Finally, the abundant and multimodal data harvested by the sensor can be further analyzed by artificial intelligence to build a digital twin model that corresponds to the real world. It will serve as a powerful platform for testing hypotheses, optimizing growth conditions, and pre-screening intervention strategies, ultimately enabling a closed-loop and smart system that responds pre-emptively to the plant's physiological state.

Author Contributions

Kuangyi Zou: conceptualization, methodology, data curation, formal analysis, validation, investigation, visualization, writing – original draft, writing – review and editing, software. **Yiran Li:** data curation. **Fei Zhou:** methodology, supervision. **Jiacheng Wang:** methodology, data curation, validation, formal analysis, writing – original draft, writing – review and editing, visualization, software. **Qianming Li:** conceptualization, writing – review and editing. **Yiding Jiao:** visualization, funding acquisition. **Xiangyi Li:** conceptualization, methodology, data curation, validation, software. **Fangyan Li:** data curation. **Hongyu Chen:** methodology, validation. **Jie Song:** data curation. **Yongle Liu:** writing – review and editing. **Shuo Yang:** data curation. **Xusong Li:** data curation. **Xinyin Cao:** data curation. **Luhe Li:** methodology. **Sicheng Huang:** data curation, formal analysis, writing – original draft, software. **Er He:** visualization. **Yuxia Zhang:** data curation. **Xinyu Liu:** data curation. **Chenyu Bai:** data curation. **Tingting Ye:** data curation. **Jiang Lu:** methodology. **Hanting Zhang:** data curation. **Yuanzhen Wang:** data curation. **Yi Gao:** visualization. **Haidong Wang:** data curation. **Ye Zhang:** conceptualization, methodology, supervision, funding acquisition, visualization, project administration, writing – original draft, writing – review and editing. **Haotian Yin:** validation.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (52422310, 22175086), the Natural Science Foundation of Jiangsu Province (BK20240169), the China Postdoctoral Science Foundation (2023M731578), and the Jiangsu Funding Program for Excellent Postdoctoral Talent (2023ZB789).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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