Plant Archives Vol. 25, No. 2, 2025 pp. 809-812 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org

DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2025.v25.no.2.112

LEVERAGING THE POTENTIAL OF PLANT TATTOO SENSORS FOR REAL-TIME MONITORING AND STRESS MANAGEMENT OF PLANT PHYSIOLOGICAL PARAMETERS: A REVIEW

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(Date of Receiving-02-06-2025; Date of Acceptance-10-08-2025)

ABSTRACT

In this era of 21st century a large proportion of Indian agriculture is still dependent on traditional methods of farming. Unlike smart farming, conventional technologies are time consuming, labor intensive and mostly wastage of resources. They are unaware of the emerging technologies which would facilitate sustainable farming and pose environmental security. For precise utilization of natural resources, it is therefore required to switch over to sustainable farming practices which would enhance resource utilization effectively and efficiently. One such noble technology used by the scientists of Iowa State University is the multimodal Plant tattoo sensors. Tattoo sensors are the wearable electro-chemical nano-sensors which are attached to various plant parts for precise determination of several plant physiological parameters. It is an emerging technology, with ongoing research in the field of precision agriculture which quantifies the parameters into legible output required for agronomic management practices at the field level. Plant tattoo sensors, conduct real-time and continuous monitoring of plant water balance and microenvironment in both short and long run. Tattoo sensors enhance resource use efficiency and promote sustainable management of abiotic stresses without compromising with the growth and productivity of the crop. Nanotechnology based wearable sensors increase the sensitivity of the sensors and provide more accurate data as compared to the traditional sensing technologies which fail to isolate individual data and might be damaged due to environmental hazards. Ergo, it is necessary to harness the optimal efficacy of the multifunctional plant tattoo sensors and provide insights on the responses in different stress conditions, thereby maintaining plant's health.

***Key words*:** Plant tattoo sensor, real-time monitoring, sustainability, stress management.

Introduction

The eco-friendly wearable plant tattoo sensors have been under research to facilitate sustainable stress management in plants (Oren *et al*., 2017). In regions of water scarcity, the measurement of drought stress in plants using plant tattoo sensors can be useful in detecting the water requirement, mainly during the critical growth stages of crops. Quantification of plant microclimate parameters including temperature, relative humidity and soil conditions (soil structure, soil texture, soil moisture content) and undertaking of appropriate management practices promote better crop yield. Existing farming technologies contribute to water pollution, soil degradation and green-house gas emissions which poses a threat to agroecology. To combat these burning issues of environmental degradation researchers are focussing on eco-friendly methods of farming. Tattoo sensors are one of those versatile nano-sensors which are fabricated in the form of tapes on the plant's body and contributes to the real-time monitoring of the plant's growth environments. The basic components of a plant wearable chemical sensor are the sensing element which must be adequately conductive to the different signalling compounds in the plant body, the substrate which should possess properties like high flexibility and stretchability, conformability, optical transparency, thermo-resistivity and chemo-resistivity, and the electronics system which would amplify and convert the transduced signal into a processed

Table 1: Morphology of plant tattoo sensors.

Sl. No.	Substrate for Plant Tattoo Sensor	Sensing Element	Application in Agriculture	Reference
1	Plastic Polymers (Ex- PDMS, PET, PVA, PI)	Reduced Graphene-oxide	Measures plant-emitted Volatile Organic Compounds (VOCs)	**Muthumalai *et al*., 2024**
2	Plastic Polymers (Ex-PET, PDMS, PI)	Au/PET film	Measures transpiration, water transport	**Yin *et al*., 2024**
3	Paper substrate backed with transfer tape	Graphene paste	Measures ethylene emission during stress conditions	**Hossain *et al*., 2023**
4	Plastic Polymers (Ex- PDMS, PI)	Graphene oxide/Graphene	Measures plant-microclimate (Ex- Humidity Sensing)	**Li *et al*., 2024**
5	Plastic Polymer (Ex- PET)	Liquid Metals (LMs)	Measures water physiological status of plants during drought stress	**Qu *et al*., 2023**

output, readable by the users (Muthumalai *et al*., 2024). This data-centric crop management approach would facilitate sustainable and eco-friendly precision farming.

Efficacy of PTS in Agriculture

The release of Volatile Organic Compounds (VOCs) from plant body occurs as a result various biotic and abiotic stress exposures in the ecosystem (Vivaldo *et al*., 2017). These signalling molecules are released in response to plant's defence system. They also release water vapour into the atmosphere via transpiration. Flexible wearable plant sensors are used for detecting the release of those VOCs or measure the dynamics of water transport within plant body.

Graphene is chosen as the sensing element due to its extreme thermal stability, light weight, flexibility and having biocompatible properties (Laera *et al*., 2023). Gold nanomaterials (Wei *et al*., 2024) and graphene oxide (GO) possess large surface area and excellent electrical conductivity which strengthens the sensor performance (Li *et al*., 2022). The oxygen-containing functional groups of GO like epoxides (-COC), carbonyl (-C=O), hydroxyl (-OH) and carboxyl (-COOH) readily interact with the smallest concentration of VOCs (Bian *et al*., 2015). The reduction of GO leads to the formation of reduced graphene-oxide (rGO), which has stronger electrical and thermal properties, rendering its use as a sensing material for humidity measurement in plant's vicinity (Liu *et al*., 2022).

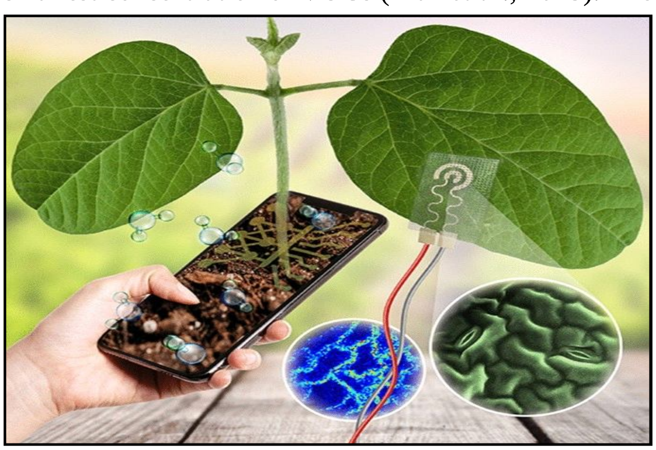

Fig. 1: Quantifiable evaluation of leaf water status using serpentine electrode (Chen *et al*., 2023).

Applications of Plant Tattoo Sensor under Different Stress Conditions

Wearable plant tattoo sensors have the ability to evaluate plant microclimates (relative leaf water content, humidity, temperature) and other bio-potential levels. As the stomata on the plant leaf surface serves as the potential bio-interface for the exchange of several VOCs, all type of wearable sensors is generally fabricated directly onto the leaf surface. Tattoo sensing elements possessing super ionic conductivity, flexibility and permeability are even capable of monitoring the electro-chemical signals at its least concentration, during minimal stress levels. Addressing the current scenario of the economics of water by the *Global Commission* (2024), more than 50% of the world's food production will be threatened due to water scarcity by 2050. So, there is a paramount need that we should switch and thrive on sustainable approaches of utilising natural resources. This accurate and potentially non-invasive skin-like tattoos can be attributed to function in different stress conditions of plants likewise-

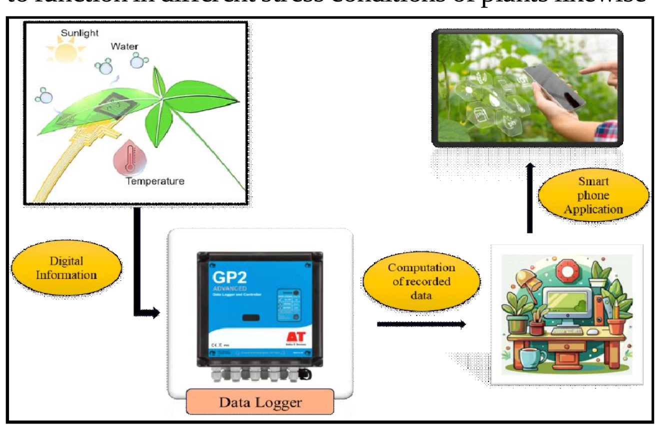

Fig. 2: Real-time monitoring of leaf-surface temperature using plant tattoo sensor.

Assessment of water transport in plants

There are specific sensors contributing towards real-time monitoring of plant water transport and thereby preventing crop losses. In an experiment, conducted in Brazil by Barbosa *et al*., 2022, impedimetric wearable electro-chemical sensors were used for on-site monitoring of loss of water content from the soybean leaves. They skilfully utilised thin films of Stand-alone-Ni structures (SANS) as their potential electrode and hence obtained the impedance measurements at certain time intervals. As water is a poor conductor of electricity, the impedance value of the electrode will be lower and electric current will flow smoothly when plant water content is high and vice-versa. This impedance data, on the loss of water from soybean leaves is restructured by various machine-learning algorithms from analog to quantitative digital data (Li *et al*., 2024), available in smartphones which are suitable for layman readout. The stand-alone Ni films determined leaf water content with optimized sensitivity of 27 $k\Omega\%^{-1}$. As stated by Lee *et al*., 2021, wilting of leaves and the plant tissue damage which occurred due to dehydration can be detected using plant tattoo sensors.

Computation of leaf surface temperature

The flexible plant tattoo sensors are capable of monitoring leaf surface temperature using spatial anisotropic temperature distribution methodology of the sensor. Temperature anisotropy is a material property in which the material exhibits directional dependence in properties due to temperature variations (Bilardello, 2016).

A temperature-sensitive resistor called thermistor, is embedded along with temperature sensors within the PDMS/PI substrate which utilises resistance mechanism to measure temperature variation. Generally, the variation occurs in a way that, there will be a decrease in resistance of the thermistor as the sap flow rate increases and vice-versa. Zhang *et al*., 2023 reported the temperature variations, based on sap flow rate, in a water melon plant. They stated that there is an increase in temperature, in the direction of sap flow within the stem vessel. The difference in temperature in between the two sensors indicated a sap flow rate of 120 $\mu L\ min^{-1}$. A linear fit model of the flow rate as a function of time gave R^2 = 0.9740, which indicated sensor's excellent adeptness.

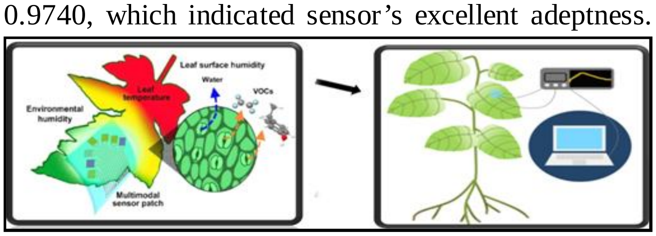

Fig. 3: Measurement of the leaf-surface humidity using multimodal tattoo sensors.

When, a positive temperature co-efficient (PTC) thermistor will be used, the heat transmitted by the thermistor will be mediated towards the direction of sap flow (Chai *et al*., 2021). Hence, real-time analysis of the sap flow rate through determination of leaf surface temperature is possible using plant tattoo sensors.

Analysis of leaf-surface humidity

Lan *et al*., 2020 portrayed the utilisation of laser-induced graphene inter-digital electrode as multi-modal humidity sensor which has capacitance change as the sensing mechanism. In an experiment conducted by Lee *et al*., 2023, nafion based sensing elements were pre-patterned on a PDMS substrate, which was taped onto the abaxial leaf surface because of its higher stomatal density. They also reported that the sensor sensitivity is 10-20% higher when placed in the abaxial leaf surface than adaxial leaf surface.

When the environmental temperature is maximum during noon, the rate of transpiration from the plant leaf surface increases, resulting in higher leaf-surface humidity. Since, a thick nafion film is known to absorb water molecules, the capacitance value of the electrode increases at night time upon water absorption from the environment and decreases during day-time upon water transpiration (Li *et al*., 2021). The ultrahigh sensitivity humidity sensor having a coating of graphene oxide/Ag nanoparticles on IDEs showed a sensitivity of 25,809 pF/% RH in the humidity range from 11% RH to 97% RH. Thus, this measure optimises the real-time and direct monitoring of leaf-surface humidity in accordance to relative leaf water content, stomatal dynamics and tailoring early stress detection and subsequent management procedures.

Conclusion and Future Directions

Multifunctional wearable tattoo sensor technologies are the emerging fields in precision agriculture and plant research. The in-situ monitoring of plant extrinsic parameters can provide us detailed insights on various plant physiological parameters. Nowadays, research focusses on the integration and incorporation of several electro-chemical wearable sensors under a single substrate, which measures the leaf water content, humidity and leaf-surface temperature altogether. Unlike the satellite imaging and remote sensing techniques for monitoring plant health, the plant tattoo sensors precisely measure all the physiological growth parameters of individual plants and hazardous amounts of agrochemicals present in their vicinity. In Gen-Agriculture generation, the data transfer process from microsensors to cloud servers are largely wireless which consumes Bluetooth, Zigbee, LoRaWAN and Wi-Fi networks for decoding the recorded data using machine learning (ML), big-data and cloud computing algorithms (Banerji *et al.*, 2023). This new frontier in agriculture provides real-time information and augments agricultural management practices.

Acknowledgements

I would like to extend my sincere gratitude to Dr Pritam Ghosh, for his continuous encouragement and assistance throughout the process.

The completion of this review could not have been possible without the unwavering guidance and support of Mr. Udit Debangshi, who is currently a Graduate Research Assistant at Kansas State University, USA. I am deeply grateful for his dedicated time, expertise and constructive criticism, which enriched this paper's quality.

Competing Interests

Authors have declared that no competing interests exist.

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