Fiber optic plant wearable sensors for growth and microclimate monitoring

Daniela Lo Presti
Department of Engineering
Università Campus Bio-Medico di Roma
Rome, Italy
d.lopresti@unicampus.it

Joshua Di Tocco
Department of Engineering
Università Campus Bio-Medico di Roma
Rome, Italy
j.ditocco@unicampus.it

Carlo Massaroni
Department of Engineering
Università Campus Bio-Medico di Roma
Rome, Italy
c.massaroni@unicampus.it

Sara Cimini
Department of Science and Technology for Humans and the Environment
Università Campus Bio-Medico di Roma
Rome, Italy
s.cimini@unicampus.it

Stefano Cinti
Department of Pharmacy
Univesity of Naples Federico II
Naples, Italy
stefano.cinti@unina.it

Rosaria D'Amato
Photonics Micro and Nanostructures Laboratory
Fusion and Technologies for Nuclear Safety and Security Department, FSN-TECFIS-MNF, ENEA
Frascati (RM), Italy
rosaria.damato@enea.it

Michele A. Caponero
Photonics Micro and Nanostructures Laboratory
Fusion and Technologies for Nuclear Safety and Security Department, FSN-TECFIS-MNF, ENEA
Frascati (RM), Italy
michele.caponero@enea.it

Laura De Gara
Department of Science and Technology for Humans and the Environment
Università Campus Bio-Medico di Roma
Rome, Italy
l.degara@unicampus.it

Emiliano Schena
Department of Engineering
Università Campus Bio-Medico di Roma
Rome, Italy
e.schena@unicampus.it

2022 IEEE International Workshop on Metrology for Industry 4.0 & IoT (MetroInd4.0&IoT) | 978-1-6654-1093-9/22/$31.00 ©2022 IEEE | DOI: 10.1109/METROIND4.0IOT54413.2022.9831698

***Abstract*—Changes in climate and the growth of population are posing a challenge in plant agricultural industries. Recent technological advances offer new tools for meeting the rising demand for food and energy worldwide. The application of wearable sensors for precision agriculture and their interfacing with plants have more recently emerged as an exciting strategy to monitor plant health. However, the use of plant wearables to improve crop productivity is in its infancy. A few wearable sensors have been designed to monitor growth, microclimate in terms of temperature (T), relative humidity (RH), and light intensity, and plant diseases. Most of these systems are based on electrical sensors that experience a change of resistance, capacitance, or impedance in response to mechanical and chemical inputs. However, some limitations, such as low sensitivity, low signal stability, and high hysteresis error, are still limiting their applications. To overcome these issues, fiber Bragg grating (FBG) technology, with its numerous advantages, can play a crucial role in plant health monitoring. FBG sensors are characterized by good metrological properties, miniaturized size, and biocompatibility, making them suitable for plant wearables development. Moreover, thanks to their easy encapsulation into flexible matrices, FBG can interface with different plant organs (e.g., leaves, stems, fruits).**

This study proposed soft plant wearable sensors based on FBG technology for plant health monitoring. A soft sensor based on FBG was used for measuring the stem elongation of a tobacco plant. In addition, two other sensors placed on the leaf were used for microclimate monitoring. The promising results open the possibility of using the proposed sensors to promptly diagnose plant health status and optimize the plant growth.

Keywords—plant wearable sensors, fiber Bragg gratings, fiber optic sensors, soft sensors, plant health, growth monitoring, microclimate monitoring.

I. Introduction

There will be nearly 10 billion people on Earth by 2050 [1]. As such, food and energy production is expected to increase by 59% - 100% to meet this rising demand [2]. Therefore, new strategies for sustainable food production are essential. Agriculture is being affected by climate changes in different ways, e.g., variations in annual rainfall, waves of temperature, modifications in pathogens, global change of atmospheric CO_2, or soil salinization. These variations negatively impact the global crop production and compromise food security worldwide [2]. The Food and Agriculture Organization (FAO) estimated 40% of crop productivity because of pesticides, diseases, and other stressors like salinity and drought [3] [4]. To reduce this loss, the 2030 Agenda for Sustainable Development considers the planet a target to be protected from degradation by managing its natural resources sustainably [5]. To accomplish this aim, new sensing technologies to monitor plant health in real-time are desired [6]. In recent years, imaging and smartphone-based techniques have been proposed for plant growth management, but these methods showed limitations for practical applications, including discontinuous measurements and low sensitivity [7]–[9].

Recently, wearable technology, largely used in human healthcare, can be leveraged for plant health monitoring due to similar sensing mechanisms and targets (e.g., deformation - ε-, temperature - T-, relative humidity - RH, pollutants, and biomarkers) [2], [6]. Plant wearable sensors are emerging as new promising solutions that are directly interfaced with the surface of plant organs as, roots, stems, and leaves to track

Authorized licensed use limited to: Mukesh Patel School of Technology & Engineering. Downloaded on July 20,2023 at 03:57:53 UTC from IEEE Xplore. Restrictions apply.

plant health in real-time for timely optimizing the plant growth and health status [2], [10]. The use of such a novel sensing technology will help in improving precision agriculture with a positive economic impact on crop production and reduction of poverty.

Plant wearables have been proposed in the literature by following single-sensor and multi-sensor approaches based on electrical and optical sensors for detecting growth, microenvironmental parameters, chemical stresses, or multifunctionalities. Electrical sensors have been used for growth detection in terms of stem elongation or fruit expansion [11]. Conductive inks and textiles have been directly printed, sputtered, or anchored on plants like bamboos, bean sprouts, and cucumbers [11], [12]. Similar systems have also been proposed for monitoring plant physiology (drought stress and water status), microclimate parameters (e.g., in terms of RH and T), and chemical stresses (e.g., air pollution and pesticides) [13], [14]. Also, optical sensors, including fiber optic technology, have been investigated for monitoring the same targets and, in some cases, these sensors have been integrated with the electrical ones for the development of multifunctional wearable sensors to meet the demands for a comprehensive monitoring of plant health status [15]. For instance, in [16], an integrated flexible multimodal system was presented for monitoring T, RH, and light intensity by exploiting electrical and optical mechanisms.

Fiber Bragg grating sensors (FBGs) are among the most popular choices for optical fiber sensors for ε and T measurements [17]. The intrinsic sensitivity of FBG to both these parameters has been mainly exploited in several fields such as structural health monitoring and healthcare [18][19] [20], [21]. In the literature, many wearable solutions have been proposed in the form of smart textiles or patches for vital signs monitoring, joint movement detections, and environmental measurements [22]–[26]. The advantages that FBGs possess over more traditional sensing methods, including their small size, passive nature, resistance to harsh environments, and corrosion, can be the key elements for extending the use of such a technology in plant monitoring [27], [28]. Last year, our research group proposed plant wearables based on FBG sensors for tomato plant growth and microclimate monitoring in terms of T and RH. However, no reference instrument was used to assess the relationship between the output changes of the growth sensor and the stem elongation [29].

Here, we proposed a novel soft sensor, similar in terms of shape to the one in [29], for monitoring stem elongation of a tobacco plant by using a contactless method as a reference. The RH and T sensors proposed in [29] have been placed on the tobacco plant leaf to further assess the wearables response to environmental conditions in a new scenario.

II. The FBG-based Plant Wearables

A. The FBG technology: background and working principle

Basically, an FBG sensor is a spatial variation of the refractive index of the core of an optical fiber [17]. It works as an optical mirror since it reflects a small portion of the light traveling along the fiber. The maximum reflection occurs at a specific wavelength (i.e., the Bragg wavelength, λ_B) and meets the Bragg condition:

$$\lambda_B = 2\,\eta_{eff}\Lambda \quad (1)$$

with η_{eff}, the effective refractive index of the fiber core, and Λ, the grating period. Eq. 1 indicates that λ_B changes ($\Delta\lambda_B$) in accordance with the two parameters mentioned above. Strains applied to the fiber cause a displacement of Λ and changes in η_{eff} because of the strain-optic effect. In the same way, FBG exposed to temperature change (ΔT) experienced changes in η_{eff} because of the thermo-optic effect and in Λ because of the thermal expansion of the fiber. These effects are described by:

$$\frac{\Delta\lambda_B(\varepsilon,T)}{\lambda_B} = (1-p_\varepsilon)\varepsilon + (\alpha + \xi)\Delta T \quad (2)$$

with p_ε, the strain-optic coefficient, α, the thermal expansion coefficient, and ξ, the thermo-optic coefficient. Eq. 2 explains how an FBG sensor is intrinsically sensitive to ε and T.

Passive and active materials can be used to encapsulate the grating. Passive polymers improve the optical fibers robustness and handleability [26], while active materials are commonly involved in the FBG functionalization for making the grating sensitive to other parameters [30], [31]. For RH sensing, for instance, hygroscopic materials are used to coat the grating since the volumetric expansions and contractions that they experience in response to changes in water vapor content induce an additional ε along the fiber and, in turn, $\Delta\lambda_B$ [32], [33].

B. The FBG-based plant wearable sensors

This study presented plant wearables for growth and microclimate monitoring of a tobacco plant. All the systems exploit the FBG properties for monitoring stem elongation, T, and RH.

a) Growth monitoring

The growth monitoring was performed by exploiting the FBG sensitivity to ε. The matrix encapsulation improves the sensor adhesion and robustness, leading to a better anchorage of the plant wearable sensor to the stem. A polymer matrix with a dumbbell shape was chosen to optimize the FBG response to ε. The matrix was obtained by the silicone-injection molding method. This technique requires the printing of a 3D mold where the FBG sensor is accommodated before the silicone pouring into the mold. The silicone was prepared by equally mixing part A and part B of Dragon Skin 20 material (Smooth-on, USA). Then, a vacuum degassing of the mixture was performed to remove all the air bubbles trapped inside, and finally, the silicone was poured into the mold to incorporate the FBG into the matrix. After the curing stage (4h at room temperature), the soft sensor for stem elongation is ready.

b) Microclimate monitoring

The microclimate monitoring was carried out by measuring T and RH values through an array of FBGs. These two environmental variables are fundamental for describing the climate conditions where the plant is growing. A bare FBG was used to detect T by exploiting the FBG intrinsic thermal

Authorized licensed use limited to: Mukesh Patel School of Technology & Engineering. Downloaded on July 20,2023 at 03:57:53 UTC from IEEE Xplore. Restrictions apply.

sensitivity, while a functionalized FBG sensor was used for RH monitoring. In this case, chitosan (CH) was used as the hygroscopic material to coat the grating (for further details about the fabrication process of the CH-coated FBG sensor, see [29]). The CH volumetric expansions/contractions activated by increments/decrements of water vapor content in the environment surrounding the sensor [34] strain/compress the grating enabling the RH sensing.

III. Tests and Preliminary Assessment

A. Experimental setup and protocol

Tobacco (*Nicotiana tabacum*) seeds were sterilized by soaking in 70% ethanol for 2 min, followed by soaking in 5% bleach for 15 min. The seeds were then rinsed five times with sterilized water. Sterilized tobacco seeds were sowed in the soil at 25 ± 1°C with a photoperiod of 16h light/8h dark. After 2 months of seed germination, the plant wearable sensor for growth monitoring was installed on the stem of a tobacco plant. Two photo-reflective markers (diameter of 6 mm, 3M™ Schotchlite™ Reflective Material 8910 Silver Fabric) were placed at the extremity of the dumbbell-shaped matrix to record reference values of elongation. An IR camera (Longruner LC26-US, image resolution 2592 x 1944 pixels) captured a photo every 5 min to spatially track the marker distance. A Raspberry Pi4 with its dedicated camera input port was used to power the IR camera and record high-resolution images in Python. Photos were captured and saved for later processing.

The plant wearables for microclimate monitoring were placed on a leaf close to the central vein to detect changes in T and RH.

A strip of filter paper was used as a substrate for the CH-coated FBG to avoid any influence of the plant transpiration process on the sensor output changes. However, the paper strip covered a small contact area of the leaf to reduce the impact on the light capture by colorful pigments.

A commercial system (BME280 by BOSCH) connected to a commercial board (M5stick-C Plus by M5stack) via I2C protocol was used to record reference T and RH values.

The output of the plant wearables was collected using an optical interrogator (HYPERION si255, Micron Optics, LUNA Inc.) at a sampling rate of 5 Hz. The reference T and RH data were collected and streamed at 10 Hz to the Raspberry Pi4. Data acquisition lasted ~40 h without any visible change in the pigment color.

B. Data analysis

Data were analyzed in MATLAB environment.

Firstly, a data synchronization was performed starting from the time at which the camera captured the first photo. Then, a subtracting technique was used to realize the T compensation of the output of the FBG sensor for growth monitoring. The compensation was carried out by subtracting the output changes of the bare FBG that detects ΔT from the ones of the FBG sensor used for monitoring stem elongation.

The reference values of T and RH were recorded by the commercial board M5stick and plotted over time, while the reference elongation values were obtained by post-processing the recorded photos using Tracker, free video analysis and modeling tool built on the Open Source Physics Java framework [35]. The main steps to obtain reference elongation value are the following:

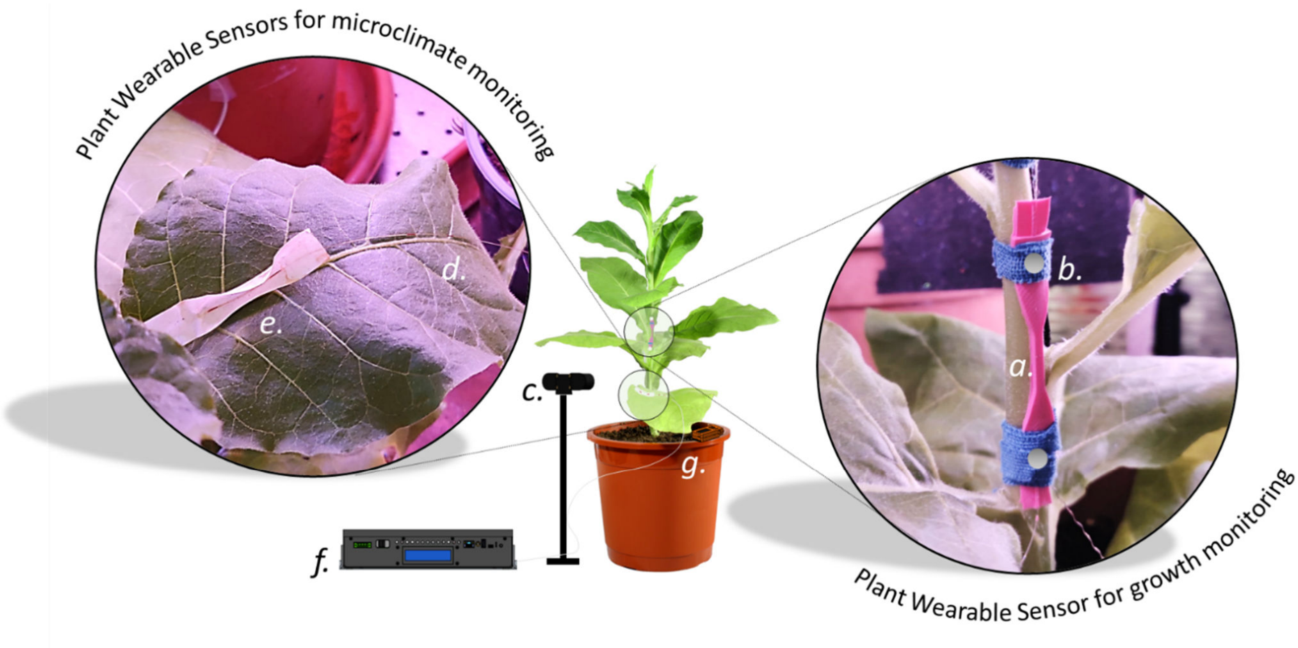

Fig. 1. Experimental setup: the FBG sensor for elongation monitoring (a) with the markers placed at the extremities of the dumbbell-shaped matrix (b), the IR camera for capturing photos over time (c), the FBG sensor for T monitoring (d), the one for RH monitoring (e), the optical interrogator (f), and the reference platform for reference T and RH values (g).

1. the position in pixel along x and y directions of each marker was extracted;

Authorized licensed use limited to: Mukesh Patel School of Technology & Engineering. Downloaded on July 20,2023 at 03:57:53 UTC from IEEE Xplore. Restrictions apply.

2. the pixel displacement over time was recorded and converted into spatial displacements (expressed in mm) by considering the dimensions in pixel of the markers in the first photo as calibration parameters;
3. the Euclidean distance between the two markers was calculated to estimate the reference plant elongation values.

C. Results

a) Growth monitoring

The output of the plant wearable sensor for stem elongation measurements is plotted over time in Fig. 2a. The reference elongation values over time are shown in Fig 2b.

As shown in Fig. 2a, the FBG sensor was able to follow the reference trend over 40 h of acquisition (Fig. 2b). Moreover, the $\Delta\lambda_B$ vs. ΔL curve showed a linear trend (Fig. 3) with an angular coefficient of 0.82 nm·mm^{-1}.

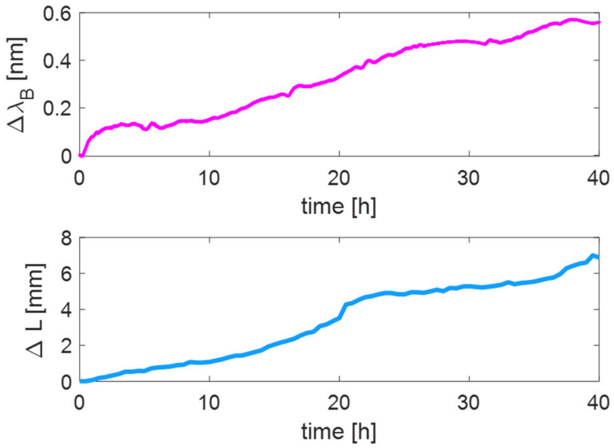

Fig. 2. The FBG output in the magenta line and the reference elongation (ΔL) values in the blue line.

Fig. 3.

The agreement between the experimental data and the model is confirmed by the high value of R^2 (> 0.98).

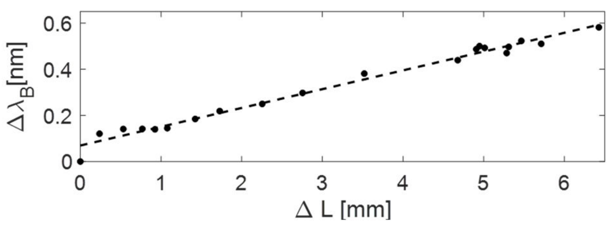

Fig. 4. The trend of $\Delta\lambda_B$ vs. ΔL considering the output of both the plant wearble sensor on the stem and the reference values recorded by the camera every 2h.

b) Microclimate monitoring:

Microclimate changes were monitored in terms of T and RH.

Focusing on T values, the trend of the bare FBG output over time and the reference T values are plotted in Fig. 4a and Fig. 4b, respectively.

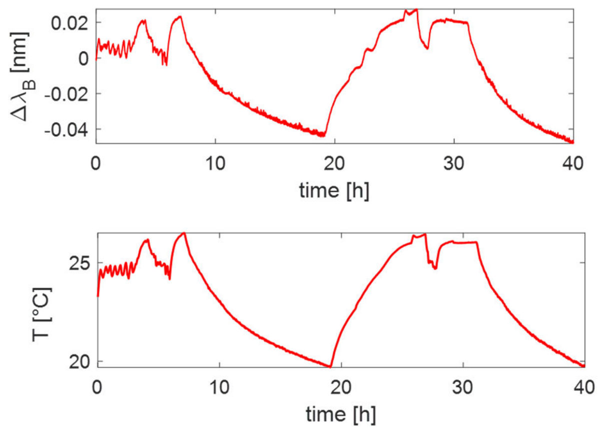

Fig. 5. The bare FBG output changes caused by ΔT over time (on the top) and the reference T values over time (on the bottom).

Focusing on RH values, the trend of the CH-coated FBG output over time and the one of the reference RH values are shown in Fig. 5a and Fig. 5b, respectively.

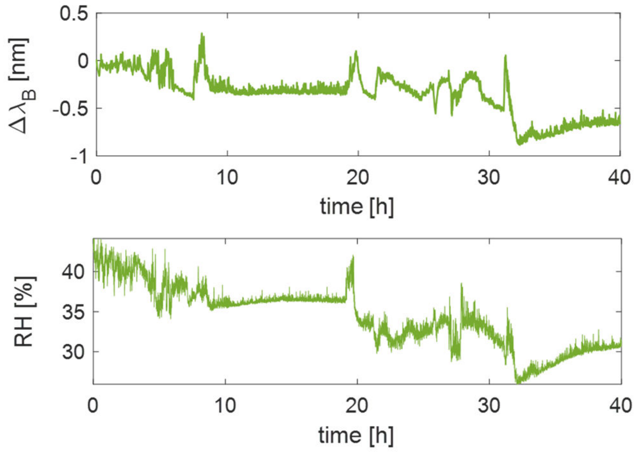

Fig. 6. The CH-coated FBG output changes caused by ΔRH over time (on the top) and the reference RH values over time (on the bottom).

Results showed that the plant wearables for microclimate monitoring were able to follow the trend of the reference T and RH signals measured by the reference instrument.

IV. Discussion and Conclusions

In the present work, we proposed plant wearables sensors based on FBG technology for growth and microclimate monitoring. This is a preliminary study on a tobacco plant. For the first time in the literature, FBG sensors were used on a tobacco plant for monitoring elongation, T, and RH. Elongation measurements were performed by placing a soft sensor along the stem, while T and RH values measurements by placing two other FBG-based sensors on a leaf. Results are promising: all the proposed sensors were able to follow trends similar to the ones of the reference instruments.

In the literature, FBG technology has been used for monitoring ε, T, and RH in other application fields such as human healthcare and structural health monitoring [31], [36]–[38] Only one study proposed the use of FBGs in the development of plant wearables on a tomato plant. The novelty of the present study compared to the one in [29] is related to the use of a reference instrument to assess the

Authorized licensed use limited to: Mukesh Patel School of Technology & Engineering. Downloaded on July 20,2023 at 03:57:53 UTC from IEEE Xplore. Restrictions apply.

capability of the growth sensor to monitor stem elongation. The agreement between the output of the FBG-based soft sensor encapsulated into the dumbbell-shaped matrix and the ones obtained by processing the images recorded by the IR camera used as a reference instrument suggests that the proposed sensor is able to detect plant growth (Fig. 3). Moreover, results showed that the plant wearables for microclimate monitoring presented in [29] were also able to detect T and RH from the leaf of a tobacco plant (Fig. 4 and Fig. 5). Indeed, the trend over time of the bare FBG for T sensing and the CH-coated FBG for RH sensing were similar to those of the reference T and RH sensors.

From an economic point of view, FBG sensors have higher costs than their electrical counterparts but better performance. The FBG data logger is usually more expensive than the commercially available data logging systems for electrical sensors. Still, the raw signal collected by FBG sensors does not require a conditioning stage offering economic advantages for FBG technology.

The numerous benefits of FBG sensors over conventional electrical sensors, such as small size, fast response, multiplexing capability, and immunity to the electromagnetic field justify the FBG cost making this technology suitable for developing ultralightweight devices able to perform distributed measurements with high reliability and low invasiveness.

Further investigations will be devoted to better investigating the performance of the proposed plant wearables over longer acquisitions in fields applications. The promising results achieved in this study suggest that plant wearables based on FBG technology may be a good solution for quantitatively assessing the influence of stressors like drought and salinity on plant morphology, physiology, metabolic responses, and biochemical alterations. The use of this novel solution on a large scale will be crucial for timely optimizing the plant health and growth, leading to improvement in monitoring parameters indicative of crop productivity.

References

[1] E. Holt-Giménez, A. Shattuck, M. Altieri, H. Herren, and S. Gliessman, "We Already Grow Enough Food for 10 Billion People... and Still Can't End Hunger," Journal of Sustainable Agriculture, vol. 36, no. 6. Taylor & Francis Group, pp. 595–598, Jul-2012.

[2] G. Lee, Q. Wei, and Y. Zhu, "Emerging Wearable Sensors for Plant Health Monitoring," Adv. Funct. Mater., vol. 31, no. 52, p. 2106475, Dec. 2021.

[3] E. C. Oerke, "Crop losses to pests," Journal of Agricultural Science, vol. 144, no. 1. Cambridge University Press, pp. 31–43, Feb-2006.

[4] S. Savary, A. Ficke, J. N. Aubertot, and C. Hollier, "Crop losses due to diseases and their implications for global food production losses and food security," Food Secur. 2012 44, vol. 4, no. 4, pp. 519–537, Jul. 2012.

[5] United Nations, "Transforming Our World: the 2030 Agenda for Sustainable Development United Nations United Nations Transforming Our World: the 2030 Agenda for Sustainable Development," 2015.

[6] A. Mohammad-Razdari, D. Rousseau, A. Bakhshipour, S. Taylor, J. Poveda, and H. Kiani, "Recent advances in E-monitoring of plant diseases," Biosensors and Bioelectronics, vol. 201. Elsevier, p. 113953, 01-Apr-2022.

[7] L. Li, Q. Zhang, and D. Huang, "A review of imaging techniques for plant phenotyping," Sensors (Switzerland), vol. 14, no. 11. Multidisciplinary Digital Publishing Institute, pp. 20078–20111, 24-Oct-2014.

[8] Z. Li et al., "Non-invasive plant disease diagnostics enabled by smartphone-based fingerprinting of leaf volatiles," Nat. Plants, vol. 5, no. 8, pp. 856–866, Jul. 2019.

[9] C. Li et al., "Measuring plant growth characteristics using smartphone based image analysis technique in controlled environment agriculture," Comput. Electron. Agric., vol. 168, p. 105123, Jan. 2020.

[10] C. C. Qu, X. Y. Sun, W. X. Sun, L. X. Cao, X. Q. Wang, and Z. Z. He, "Flexible Wearables for Plants," Small, vol. 17, no. 50. John Wiley & Sons, Ltd, p. 2104482, 01-Dec-2021.

[11] W. Tang et al., "Rapid fabrication of wearable carbon nanotube/graphite strain sensor for real-time monitoring of plant growth," Carbon N. Y., vol. 147, pp. 295–302, Jun. 2019.

[12] J. M. Nassar, S. M. Khan, D. R. Villalva, M. M. Nour, A. S. Almuslem, and M. M. Hussain, "Compliant plant wearables for localized microclimate and plant growth monitoring," npj Flex. Electron., vol. 2, no. 1, pp. 1–12, Sep. 2018.

[13] F. Zhao, J. He, X. Li, Y. Bai, Y. Ying, and J. Ping, "Smart plant-wearable biosensor for in-situ pesticide analysis," Biosens. Bioelectron., vol. 170, p. 112636, Dec. 2020.

[14] J. P. Giraldo, H. Wu, G. M. Newkirk, and S. Kruss, "Nanobiotechnology approaches for engineering smart plant sensors," Nature Nanotechnology, vol. 14, no. 6. Nature Publishing Group, pp. 541–553, 05-Jun-2019.

[15] R. M. Galatus, R. Papara, L. Buzura, A. Roman, and T. Ursu, "Wearable multi-sensor for plant monitoring, based on fluorescent fibers," in https://doi.org/10.1117/12.2559993, 2020, vol. 11361, p. 36.

[16] Y. Lu et al., "Multimodal Plant Healthcare Flexible Sensor System," ACS Nano, vol. 14, no. 9, pp. 10966–10975, Sep. 2020.

[17] T. Erdogan, "Fiber grating spectra," J. Light. Technol., vol. 15, no. 8, pp. 1277–1294, Aug. 1997.

[18] C. Massaroni, M. A. Caponero, R. D'Amato, D. Lo Presti, and E. Schena, "Fiber bragg grating measuring system for simultaneous monitoring of temperature and humidity in mechanical ventilation," Sensors (Switzerland), vol. 17, no. 4, p. 749, Apr. 2017.

[19] D. Lo Presti et al., "Smart Textile Based on 12 Fiber Bragg Gratings Array for Vital Signs Monitoring," IEEE Sens. J., vol. 17, no. 18, pp. 6037–6043, Sep. 2017.

[20] D. Lo Presti et al., "Fiber bragg gratings for medical applications and future challenges: A review," IEEE Access, vol. 8, pp. 156863–156888, 2020.

[21] Z. Liu, P. Liu, C. Zhou, Y. Huang, and L. Zhang, "Structural health monitoring of underground structures in reclamation area using fiber bragg grating sensors," Sensors (Switzerland), vol. 19, no. 13, p. 2849, Jun. 2019.

[22] D. Lo Presti et al., "Cardio-respiratory monitoring in archery using a smart textile based on flexible fiber bragg grating sensors," Sensors (Switzerland), vol. 19, no. 16, p. 3581, Aug. 2019.

[23] D. Lo Presti, F. Santucci, C. Massaroni, D. Formica, R. Setola, and E. Schena, "A multi-point heart rate monitoring using a soft wearable system based on fiber optic technology," Sci. Rep., vol. 11, no. 1, pp. 1–10, Oct. 2021.

[24] D. Lo Presti et al., "An fmri compatible smart device for measuring palmar grasping actions in newborns," Sensors (Switzerland), vol. 20, no. 21, pp. 1–16, Oct. 2020.

[25] D. Lo Presti et al., "A multi-parametric wearable system to monitor neck movements and respiratory frequency of computer workers," Sensors (Switzerland), vol. 20, no. 2, p. 536, 2020.

[26] D. Lo Presti et al., "Wearable system based on flexible fbg for respiratory and cardiac monitoring," IEEE Sens. J., vol. 19, no. 17, pp. 7391–7398, Sep. 2019.

[27] L. Dziuda, F. W. Skibniewski, M. Krej, and J. Lewandowski, "Monitoring respiration and cardiac activity using fiber Bragg grating-based sensor," IEEE Trans. Biomed. Eng., vol. 59, no. 7, pp. 1934–1942, 2012.

[28] M. Fajkus et al., "MR Fully Compatible and Safe FBG Breathing Sensor: A Practical Solution for Respiratory Triggering," IEEE Access, vol. 7, pp. 123013–123025, 2019.

[29] D. Lo Presti et al., "Plant wearable sensors based on FBG technology for growth and microclimate monitoring," Sensors, vol. 21, no. 19, p. 6327, Sep. 2021.

[30] D. Lo Presti, C. Massaroni, and E. Schena, "Optical Fiber Gratings for Humidity Measurements: A Review," IEEE Sens. J., vol. 18, no. 22, pp. 9065–9074, Nov. 2018.

Authorized licensed use limited to: Mukesh Patel School of Technology & Engineering. Downloaded on July 20,2023 at 03:57:53 UTC from IEEE Xplore. Restrictions apply.

[31] D. Lo Presti et al., "A Magnetic Resonance-Compatible Wearable Device Based on Functionalized Fiber Optic Sensor for Respiratory Monitoring," IEEE Sens. J., vol. 21, no. 13, pp. 14418–14425, Mar. 2021.

[32] Y. Miao et al., "Relative humidity sensor based on tilted fiber Bragg grating with polyvinyl alcohol coating," IEEE Photonics Technol. Lett., vol. 21, no. 7, pp. 441–443, Apr. 2009.

[33] T. L. Yeo, T. Sun, and K. T. V Grattan, "Fibre-optic sensor technologies for humidity and moisture measurement," Sensors and Actuators, A: Physical, vol. 144, no. 2. pp. 280–295, 2008.

[34] D. Lo Presti, M. Zaltieri, R. D'Amato, M. Caponero, C. Massaroni, and E. Schena, "Feasibility assessment of an FBG-based soft sensor embedded into a single-use surgical mask for respiratory monitoring," in 2021 IEEE International Workshop on Metrology for Industry 4.0 and IoT, MetroInd 4.0 and IoT 2021 - Proceedings, 2021, pp. 166–171.

[35] D. Brown, W. Christian, and R. Hanson, "Tracker Video Analysis and Modeling Tool for Physics Education," OSP, 2021. [Online]. Available: https://physlets.org/tracker/. [Accessed: 11-Feb-2022].

[36] J. Di Tocco et al., "A Wearable System Based on Flexible Sensors for Unobtrusive Respiratory Monitoring in Occupational Settings," IEEE Sens. J., vol. 21, no. 13, pp. 14369–14378, Nov. 2021.

[37] D. Lo Presti, C. Massaroni, and E. Schena, "Optical Fiber Gratings for Humidity Measurements: A Review," IEEE Sens. J., vol. 18, no. 22, pp. 9065–9074, Nov. 2018.

[38] D. Lo Presti et al., "Agar-Coated Fiber Bragg Grating Sensor for Relative Humidity Measurements: Influence of Coating Thickness and Polymer Concentration," IEEE Sens. J., vol. 19, no. 9, pp. 3335–3342, 2019.

Authorized licensed use limited to: Mukesh Patel School of Technology & Engineering. Downloaded on July 20,2023 at 03:57:53 UTC from IEEE Xplore. Restrictions apply.