A “Living Sensor” Based on Sansevieria Plant for Measurement of UV-A Radiation

Carlo Trigona, *Member, IEEE*, Ivana Puglisi, Andrea Baglieri, and Anna Maria Gueli

***Abstract*— This research activity concerns the development of a sensor based on Sansevieria plants to measure UV-A radiation. The proposed approach is based on soils and plants together with the metabolic processes and bacterial activities involved in such organisms. This generation of devices aims to overcome silicon-based solutions that cause environmental pollution with CO_2 emissions during manufacturing and issues of nonbiodegradability and toxicity at the dissemination or end-of-life phases. The sensor here studied and characterized presents no CO_2 emissions during the production, considering the absence of manufacture and foundries processes, and it is also capable to meet the zero-CO_2 condition by reducing the amount of carbon dioxide already present in the environment through natural photosynthetic processes. The living sensor based on the Sansevieria and its working principle is studied for the first time in the literature, together with the analysis of radiation in the bandwidth of 350–400 nm, the metrological characterization, the features, and influences analysis. The results highlight the suitability of the Sansevieria as a self-generating, battery-less sensor based on the metabolic processes in the living system, soil, and plant, as a function of the measurand. It is worth noting that the approach followed here has the prerogative of being simple, low-cost, nontoxic, biodegradable, environmentally friendly, and mimetic with a perspective of achieving a huge jump in the development of green measuring systems.**

***Index Terms*— Chemo-electrical transduction, living organisms, plant-based sensor, Sansevieria, sensor characterization, UV radiation measurements.**

I. Introduction

TECHNOLOGICAL innovation in the field of measurement systems and electronic devices is certainly one of the most interesting trends of recent years [1], [2], specifically in terms of research and investments made by companies and academic institutions. The technological landscape often changes very rapidly according to the advancements and innovations in cutting-edge alternative technologies [3], [4].

Focusing on silicon-based devices, it should be noted that the semiconductor industry’s carbon emissions are high. Unfortunately, the manufacture of these devices represents an ungreen approach: although some of the fabrication energy comes from renewable sources, most of it requires the use of fossil fuels such as carbon and gas. In addition, some chipmakers emit a significant amount of pollutants [5]. An increase in gas emission has been observed in recent years, with values more than doubling in two years and around 15 million tons of CO_2 equivalent in a single year for a semiconductor and silicon/micro electro-mechanical systems (MEMS) foundry [6], [7]. Considering these procedures together with the metal layers used in integrated sensors, an emission of about 11.3-kg CO_2e/kg can be observed [8].

The eco-friendly aspect and biodegradability of these devices are a key point: the silicon cannot be absorbed naturally [9] and for this reason, significant efforts have been made to reduce carbon emissions [7], [10] by developing new micro and nano-fabrication techniques for sensors and MEMS devices based on biodegradable polymers [11], which offer an alternative that is not only more sustainable but also less expensive and more suitable for future applications. In order to reduce the emissions correlated with the fabrication process, obtain carbon neutrality and a fully biodegradable device, the polycaprolactone or polylactide material can be taken into consideration as low emission (<5.5-kg CO_2e/kg) [12] of pollutants, biocompatible and biodegradable synthetic and bio-based polymers [13], [14]. Literature also shows a tendency to use biopolymers as substrates, e.g., cellulose or bacterial cellulose [15], [16], [17] for sensors and mobile devices [17], [18]. Such solutions, through these compounds, imply near-zero CO_2 emissions and near 100% biodegradability. To implement sensing systems, however, the compound must include various additive layers such as metal [19], carbon black [20], carbon nanotubes [21], or doping with ZnO, which implies an increase in emissions [22]. As a consequence, biodegradability decreases as a function of the mixed materials [23]. With the aim to increase the greenness of the entire device, literature shows the possibility of using the sensing capabilities of soils in order to develop sensors based on living microorganisms. In [24], the soil was used as a temperature sensor through the application of electrogenic bacteria and a chemo-electrical transduction process. This solution can be considered fully biodegradable and without emissions of CO_2 considering the absence of a fabrication phase. In line with the latter, this article will address a highly innovative aspect in the context of green devices by presenting a paradigm, which goes beyond the “classical” technologies previously described. The idea is to adopt soils and plants as “living” sensors and self-generating devices which guarantee the development of completely biodegradable systems with no CO_2 emissions during the production, considering the absence of manufacturing and foundries processes, but also capable to absorb the CO_2 already present in the environment

Manuscript received 6 February 2023; accepted 17 March 2023. Date of publication 10 April 2023; date of current version 26 April 2023. This work was supported in part by PIAno di inCEntivi per la RIcerca di Ateneo (PIACERI), Starting Grant, Linea 3—MULTIfunctional MEthods for the next generation of smarT mEasuRement systems (MULTIMETER) Project and Linea 2—CoLor rEndering Accuracy in cultuRal heritage (CLEAR). The Associate Editor coordinating the review process was Dr. Valentina Bianchi. *(Corresponding author: Carlo Trigona.)*

Carlo Trigona is with the DIEEI, Dipartimento di Ingegneria Elettrica Elettronica e Informatica, University of Catania, 95125 Catania, Italy (e-mail: carlo.trigona@dieei.unict.it).

Ivana Puglisi and Andrea Baglieri are with the DI3A, Dipartimento di Agricoltura, Alimentazione e Ambiente, University of Catania, 95123 Catania, Italy.

Anna Maria Gueli is with the DFA, Dipartimento di Fisica e Astronomia “Ettore Majorana”, University of Catania, 95123 Catania, Italy.

Digital Object Identifier 10.1109/TIM.2023.3265746

(i.e., through photosynthetic processes). Focusing the attention on plants, the principle behind living sensors concerns the possibility of using the "natural" sensing properties of these vegetal organisms in order to implement sensors based on chemo-electrical transduction thus obtaining an output voltage as a function of the specific measurand, when other parameters such as the microorganism, the mineralogy of the soil, and other physical quantities of interest remain unchanged or naturally filtered by the specially considered plant. It should be noted that the choice of a specific plant and soil is crucial during the implementation of the living sensor. The sensing properties of plants are extensively studied in the context of plant biology and various studies have been conducted in the context of electrophysiology [25], and, as shown in [26], the adoption of plants as living sensors can be considered as a suitable green paradigm in the instrumentation and measurements context.

Baluska [27] investigate electrical signals in long-distance communication in plants giving particular emphasis to action potentials. Various case studies were considered, including the analysis of action potentials and variation potentials recorded in the stem of *Helianthus annuus*. The excitation was imposed through an electrical signal and the variation potentials were observed by using wounding as stimulation. An output voltage in the order of 50 mV was observed and a spatial analysis as a function of electrodes implanted in the plant was also conducted. The ion mechanism of action potentials was addressed by involving Ca^{2+}, Cl^{-}, and K^{+} fluxes and considering various plants including *Salix viminalis*. Both potentials have been widely studied as electrical activities in plants also from the modeling point of view, in particular, in [28], the primary responses of a plant to changes in environmental factors and the potential propagation were pursued with the mathematical model of action potential propagation. A dynamical model which is in line with the propagation theory in electrical wires and systems of telegraphers was addressed in [29]. In particular, in the latter article, a voltage signal was applied and the propagation of the waveform was analyzed and modeled. The model of a plant, considering a differential equation with time and space derivatives, was studied as a biological wire, and a dc voltage of 9 V was applied analyzing the propagation effect in the plant. Various aspects were considered such as ion species, such as K^{+} and Na^{+} or H^{+}, K^{+}, and Cl^{-}, the maximum conductance, the channel open probability, electrical parameters of the membrane, and the external stimulus to excite the system. This external signal could represent a physical quantity under analysis, including thermal variation as proposed in [30] where authors addressed the study of electrical signaling in *aloe vera* induced by localized thermal stress. In this article, the authors investigate the propagation speed of thermally induced action potentials. A maximum voltage variation of about 40 mV was observed in presence of a 0 °C thermal shock with electrodes installed inside the plant at 1 cm of distance. However, in the perspective, to conceive less invasive electrical contacts, an electrical configuration with electrodes installed inside the soil can be considered. For example, as described in [24], where the possibility of using soil as a sensor, with implanted electrodes, was demonstrated. The conversion principle, widely studied in terms of X-ray irradiation, heating procedure, and enzymatic activities [31] was based on the modification of the metabolic processes of natural microorganisms within the soil as a function of the external measurand. Trigona et al. [32] propose a plant-based sensor for UV-A radiation measurements realized by using a *Dimorphotheca ecklonis* as a living sensor and, in this case, adopting weak invasive contacts through electrodes inside the soil. The transduction principle is based on the biochemical actions of cryptochrome. A preliminary study was presented together with the performance of the proposed device. This article improves the state of the art by presenting, for the first time, a sensor based on *Sanseviera cylindrica* to measure the radiation in the band 350–400 nm and having the prerogative of being self-generating, simple, low-cost, nontoxic, biodegradable, environmentally friendly, and mimetic in the perspective to achieve a gigantic step in the realization of the green economy. Compared with the previous paper [32], this article represents an evolution of the research activity with the goal of developing better-performing living sensors with more interesting features and exhaustive characterization, performances, and influences. The features arouse interest both in the context of environmentally friendly devices and for applications that can span in the context of security, cultural heritage, smart home, and smart agriculture. It is worth noting that, to the best of our knowledge, this is the first demonstration of the generating sensing properties of this class of plant-soil devices. This article is structured as follows. Section II will describe the working principle and the experimental setup used for the characterization. The obtained results are presented in Section III, which includes the analyses in terms of applied UV-A irradiation to the plant, the metrological characterization of the living sensor, and the study in terms of influences. Final remarks and future trends are given in Section IV.

II. WORKING PRINCIPLE AND SETUP

A. *Sansevieria Cylindrica Description*

The plant used in the study was a *Sansevieria cylindrica*, also known as *Dracaena angolensis* and commonly named Sansevieria. It is a *Crassulaceae* plant native to subtropical African regions, belonging to the genus *Dracaena* (family *Asparagaceae*) [33]. It is an ornamental plant as it is very easy to cultivate and take care of indoors if given bright light and a moderate amount of water being a drought-tolerant species. It presents interesting properties in terms of growth over time and it presents various characteristics including slow-growing which can be also in the order of ≈10 mm/year. *Crassulaceae* plants are also drought-resistant plants in which the leaves, stem, and roots can be considered as water-storing tissues, characterized by a typical carbon fixation pathway known as Crassulacean acid metabolism (CAM), which evolved in plants adapted to arid conditions and allows them to photosynthesize during the day and only exchange gases during the night [34]. For its physiological characteristics, *Sansevieria cylindrica* may be a suitable prototype for the indoor UV-A living sensor model. Moreover, *Sansevieria asparagaceae* showed to be a good candidate to produce a stable output voltage,

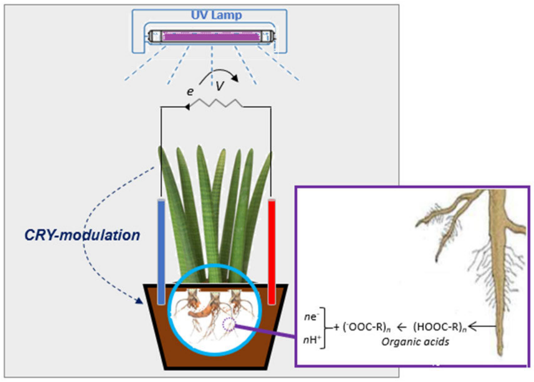


Fig. 1. UV-A radiation detection in *Sansevieria cylindrica*. The inset evinces the organic acids and the chemical process at the level of roots.

allowing to harvest of energy from the plant microbial fuel cells (PMFCs), a green technology generating energy through an electrochemical process based on the degradation of plant roots via bacterial action [35].

B. Radiation Detection Principle in Sansevieria Cylindrica

Focusing the attention on the working principle, Fig. 1 shows a schematization of the plant and the transduction principle which will be used to measure the UV-A radiation. In particular, considering the recent studies, the *Dimorphotheca ecklonis* was successfully used as a living sensor for UV-A radiation measurements, and the mechanism hypothesis was linked to the photoexcitation of cryptochromes through processes involving electron transfer and flavin reduction [32]. Plant cryptochromes are UV/blue light photoreceptors that play a pivotal role in the growth, development, and stress responses of the plant [36]. It was shown that in *Eriophorum angustifolium* and *Narthecium ossifragum* the UV radiation modified the plant metabolism, causing a change in the net efflux of root rhizodeposition, which is the soil fraction directly influenced by soil microorganisms and root exudates [37]. These latter may strongly influence the physiochemical properties of the rhizosphere, modifying the soil redox potential [38]. The soil is a complex entity made of mineral and organic substances, the latter made of residual necromass, living biomasses such as microorganisms and macroorganisms, and humic substances (the most stable component). One of the humic substance fractions, the humin, may be considered as a versatile redox mediator to enhance multiple microbial redox metabolisms under anaerobic conditions such as reductive dehalogenation, dissimilatory iron reduction, dissimilatory nitrate reduction to ammonium, and denitrification [39]. Thus, the change in the soil redox potential due to the chemical reactions induced by microorganisms and sustained by humin may explain the voltage developed between the two electrodes. The compounds in root rhizodeposition, especially sugars and organic acids, may differ depending on the type of plant metabolism [40]. In CAM plants, such as *Ananas comosus* and *Sedum alfredii* root exudates and their qualitative composition showed a high amount of succinate, malate and citrate, and organic acids which can affect the electrochemical processes in the soil [41].

An open-circuit voltage and current were continuously measured to determine the output power of the PMFCs by using three different plant prototypes characterized by different metabolisms (C3, C4, and CAM). Among these plants, the CAM plant *Chlorophytum comosum* registered the highest maximum power density at 30.39 $\mathrm{mW/m^2}$ [42].

Moreover, CAM plants have the advantage to be able to generate rhizodeposition even in dry soil conditions as they are drought-resistant [43]. Based on these evidences, our results suggest that *Sansevieria cylindrica* may be a suitable plant for the UV-A radiation detection, affecting root exudates production which may modify the soil redox potential at each dry condition, thus determining a measurable signal among cathode and anode depending on UV-A intensity.

C. Experimental Setup

In order to study and characterize the living sensor, a suitable experimental setup was conceived. Fig. 2(a) shows a schematization of the entire system which is composed of the following.

1) A *Sansevieria cylindrica* has 15 stems with a length of about 290 mm.
2) A UV-A source generator, Labino 135 series 35 W.
3) A fixed stand with variable height in order to change the irradiance level. The correlation between distance and irradiation amplitude will be described in Section III-C.
4) A UV light meter PCE-UV34 measurement system equipped with an external sensor that operates on a wavelength of 290–390 nm.
5) The sensor is realized with two electrical contacts (anode and cathode) located inside the soil, in order to electrically connect the plant. The choice of the electrodes is motivated in order to obtain the maximum redox potential, which in turn will increase the measurable output signal of the sensor.
6) A laptop with a LabVIEW[1] routine is used to acquire the output voltage coming from the plant. The adopted board is the NI USB-6366, a multifunction I/O device having eight differential analog input channels with other digital sections and counters.
7) An automatic measurement system was implemented by using a DAQ assistant block with a suitable differential analog input in order to acquire the voltage signal coming from the plant. An iterative routine, through a while loop, was considered together with a virtual oscilloscope and a memorization block employed through a write-to-measurement file in order to save, as a CVS file, the measurements for the postprocessing of the data, executed by using MATLAB.[2]

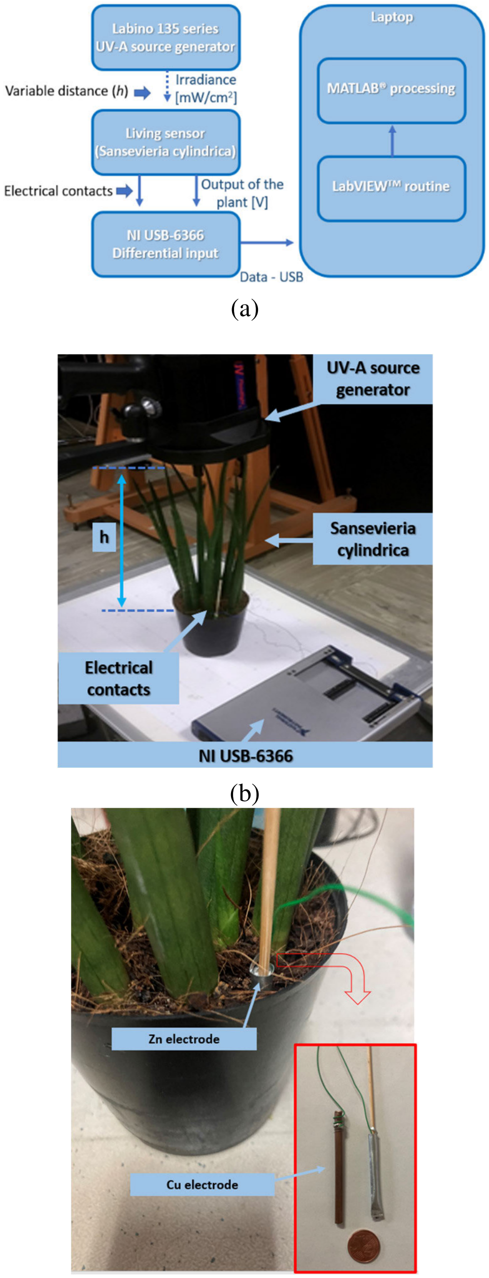
Fig. 2(b) shows the *Sansevieria cylindrica* and the setup which was used during the measurement campaign. Fig. 2(c) shows a zoomed-in view of the electrodes.

It is worth noting that the depth of the inserted electrodes was ∼6 cm, and the gap between electrodes corresponds

---

[1] Trademarked.

[2] Registered trademark.



(a)

(b)

(c)

Fig. 2. Block diagram of (a) characterization measurement system and (b) experimental setup. "h" represents the distance between the plant used as sensor and the UV-A source. (c) Zoomed-in view of the electrodes, both installed in the soil. It was hydrated with 50 mL of water in presence of an indoor temperature of about 23 °C.

to ∼4 cm. Both electrodes were arranged inside the soil and, in particular, they were intercalated orthogonally to the ground level. Regarding the location of the electrodes, the position as respect roots, the distance between both the contacts and the depth, and the choice was strictly correlated with an optimization procedure conducted before the characterization of the living sensor.

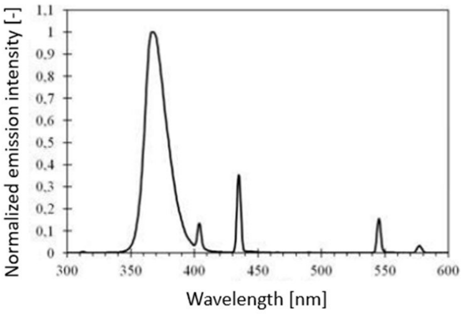


Fig. 3. Normalized emission intensity of the UV-A source.

D. Description of UV-A Source and Detector

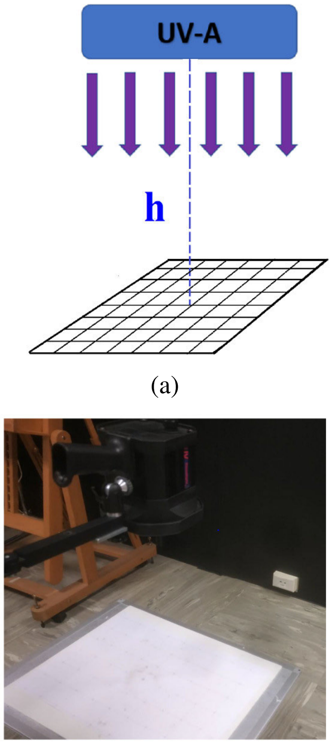
UV radiation covers the portion of the electromagnetic spectrum with a wavelength between 100 and 400 nm and is divided into three main categories: UV-A (315–400 nm), UV-B (280–315 nm), and UV-C (100–280 nm). In general, the penetration capacity and thus the "dangerousness" of UV rays increases as the wavelength decreases and, consequently, as the frequency increases. UV-C radiation has the highest energy, and therefore, the most damaging but it is this radiation damage that determines its use for disinfection due to its germicidal properties [44], [45]. The sun represents the natural source of the entire spectrum of UV radiation but all UV-C and 90% of UV-B emissions are absorbed by the atmosphere while UV-A radiation reaches the earth's surface virtually unchanged. Based on the scientific literature, the WHO has identified nine diseases closely linked to exposure to ultraviolet radiation reaching the earth's surface. The risk from UV radiation is considered on the basis of the Global Solar Index (UVI): the higher the index value, the greater the potential damage to skin and eyes [46], [47]. Interest in UV-A radiation and, in particular, both irradiation intensity and spatial distribution, also concerns other fields of application such as, for example, esthetics for artificial tanning [48] and preventive conservation of works of art [49]. This latter case represents a possible application of interest of the device presented. Considering the objectives of the research, the first step was to find a radiation source with UV-A emission (Fig. 3).

The Labino^2 Duo-UV device was therefore chosen, based on two key components: the Labino DUV-35 W Gas Discharge Bulb (MPXL technology) and the Labino Trigger Ballast (Electronics). This lamp reaches full power in 5–15 s and can be switched ON and OFF whenever used, without precooling. The model used, PS135 UV (Pistol Handle Short) Floodlight has a beam with a distribution angle of about 45° and an irradiance of about 4000 μW/cm^2 at 38 cm (after 15″).

Irradiance measurements were carried out with the PCE-UV34 radiation meter, a very versatile device thanks to its external sensor consisting of a photodiode with the UV correction filter. It operates over a wavelength range of 290–390 nm, has a resolution of 0.001 mW/cm^2, an accuracy of ±4%, and a response time of 0.4 s.

III. EXPERIMENTAL RESULTS

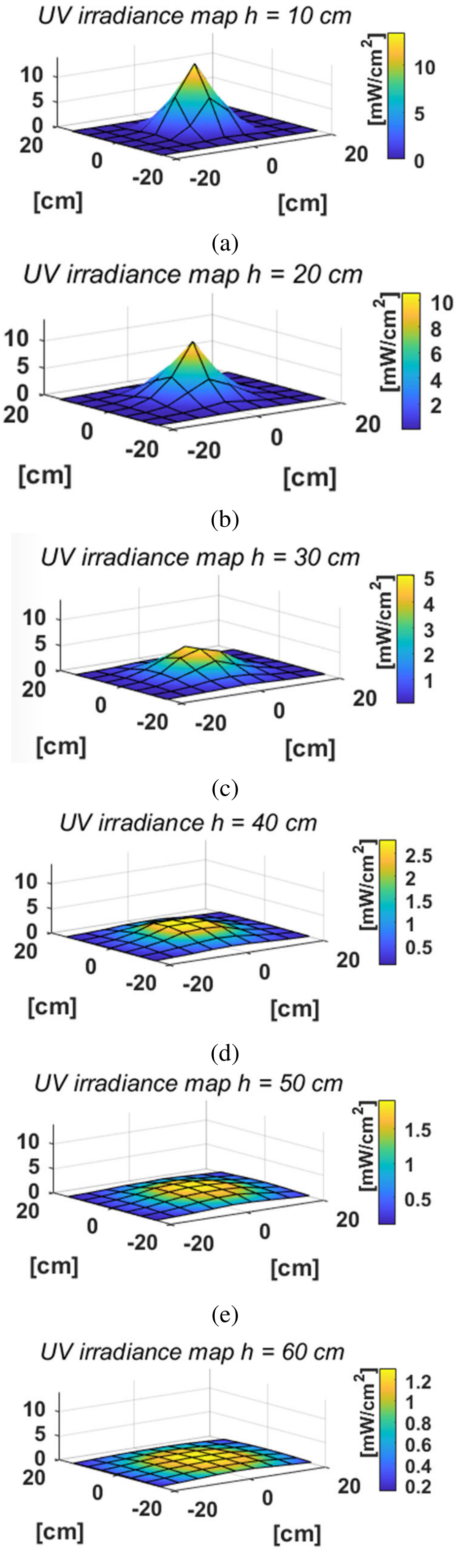
The *Sansevieria cylindrica* was irradiated with the UV-A source described in Section II and the amplitude of irradiation was changed by modifying the distances (h) between the plant and the irradiation source. The measurement of applied



(a)

(b)

Fig. 4. (a) Sketch and (b) photograph of the setup used for the reconstruction of irradiance maps.



(a)

(b)

(c)

(d)

(e)

(f)

Fig. 5. Analysis of the UV irradiance applied to the *Sansevieria cylindrica*: amplitude and spatial distribution considering distances in the interval (a) 10, (b) 20, (c) 30, (d) 40, (e) 50, and (f) 60 cm.

irradiation, the spatial distribution, and the intensity analysis will be here described and will represent propaedeutic steps for the metrological characterization presented in the next section.

A. UV-A Irradiance Spatial Distribution

Measurements for the evaluation of the distribution of UV-A irradiance intensity at different distances were carried out by considering a 30-cm-square surface on which a grid with a 5-cm pitch was drawn (see Fig. 4). Irradiance measurements were taken at each grid element using the UV meter's external sensor, and the data were processed to obtain the UV irradiance maps shown in the next section.

B. Measurements of Applied UV-A Irradiation

Fig. 5 shows the plot of the irradiance values as spatial distribution on the surface (map) at different distance values [see h in Fig. 4(a)] from 10 to 60 cm with a step, manually changed, of 10 cm.

The study evinces a decrement in the applied irradiance as a function of the distance. In fact, a maximum value of 13.5 mW/cm^2 irradiance was observed at the central point of the surface at a distance of 10 cm, decreasing to 1.3 mW/cm^2 at a distance of 60 cm (see Table I). An inverse square relationship between irradiation and source distance can be observed. Fig. 6 shows the plot of the irradiance values as a function of the distance of the source in the range between 10 and 60 cm with the behavior of the obtained quadratic fit.

C. Characterization of the Living Sensor

The measurements were performed in order to demonstrate the chemo-electrical transduction process and the response of the sensor as a function of the impressed level of measurand, in accordance with the working principle presented in Section II.

TABLE I

VALUES OF IRRADIANCE MEASURED AT THE CENTER OF THE SURFACE AT VARYING SOURCE-DETECTOR DISTANCE

Distance (cm)	*Irradiance (mW/cm^2)*
10	13.47
20	10.64
30	5.08
40	2.80
50	1.91
60	1.30

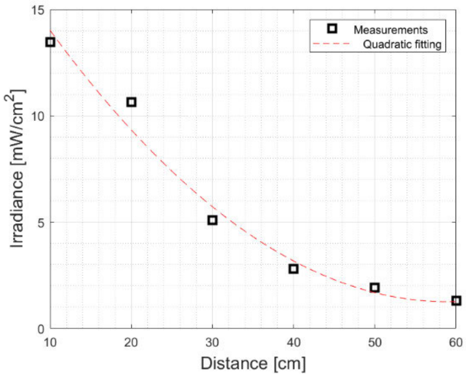


Fig. 6. Irradiance amplitude in the bandwidth of 350–400 nm as a function of the distance (h). The graph includes the quadratic fitting equation.

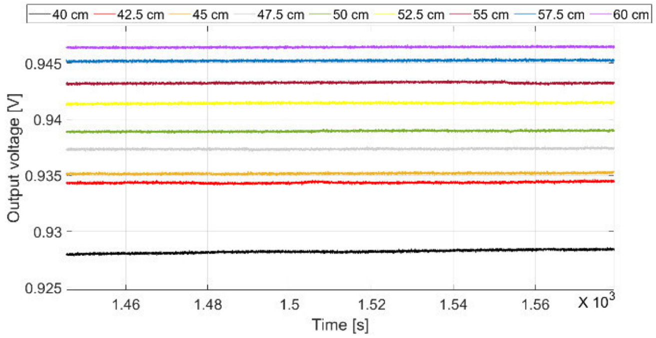


Fig. 7. Evolution of the output voltage across the electrodes considering various distances between the plant and the UV-A source.

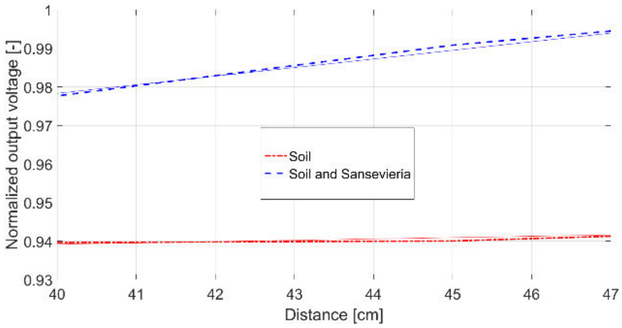


Fig. 8. Output voltage across the electrodes as a function of various distances between the plant and the UV-A source for the soil and the soil together with the *Sansevieria cylindrica*.

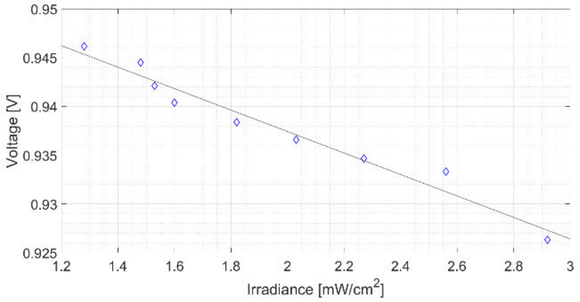


Fig. 9. Output voltage as a function of the UV-A applied radiation level. The measurement range corresponds to 1.2–3 mW/cm^2.

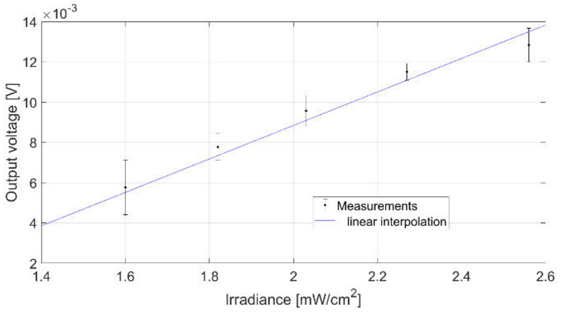


Fig. 10. Calibration diagram of the *Sansevieria cylindrica* used as a living sensor. The graph includes linear interpolation and evinces the correlation between the output voltage and the measurand.

Fig. 7 shows the output voltage generated across the two electrodes installed inside the soil as a function of various distances between the plant and the UV-A source. The range between 40 and 60 cm which corresponds to about 3 and 1.2 mW/cm^2 was considered, respectively. The graph shows a voltage output of about 0.947 V for a level of radiation of about 1.2 mW/cm^2, while a decrement can be observed for higher values of UV-A level. The minimum value corresponds to about 0.928 V which is related to a distance of 40 cm and a radiation level of about 3 mW/cm^2. A time window of 140 s was considered, and the measurements were conducted maintaining controlled conditions in terms of temperature, humidity, and irrigation level.

Fig. 8 shows the output voltage considering the soil and the soil with the plant as a function of the distance. The normalization was conducted with respect to the maximum value of voltage. The graph evinces that only in presence of the soil and the plant the device is capable to measure the level of UV-A radiation.

In presence of soil the system is unable to measure the physical quantity of interest and an almost constant voltage can be observed. This result also confirms the working principle and the importance to adopt the Sansevieria as the living organism to conduct the measurements. Fig. 9 shows the output voltage as a function of the level of UV-A radiation from 1.2 to 3 mW/cm^2. The result includes the points which represent the mean value and the linear interpolation. A voltage decrement can be observed by increasing the amplitude of applied radiation. Fig. 10 shows the calibration diagram of the *Sansevieria cylindrica* as a function of the applied UV irradiance. The graph includes the measurements and the linear interpolation. Each point of the graph represents the difference

TABLE II

COMPARISON OF THIS ARTICLE WITH OTHER TRADITIONAL INDUSTRY SENSORS

Model	**Price [$]**	**Device**	**Spectral response [nm]**	**Field of view [°]**	**Power [mW]**	**Response time [ms]**	**Sensitivity** [mV/ mW/cm^2]	**Resolution** [mW/cm^2]	**Meas. Range** [mW/cm^2]	**Accuracy** [%]	**Thermal drift [%/°C]**	**Reference**
SKU 421	430	GaAsP	315-400	80	700	<10	100	0.004	10	. ±5	±0.001	[50]
RK200-07	320	Si-Al	280-400	30	100	≤1k	100	0.016	20	. ±5	±0.08	[51]
GUVA S12SD	10	GaN	240-370	130	0.5	<0.5k	60	0.009	15	±6	±0.08	[52]
UVA-BTA	160	Si-metal	320-390	-	-	2k	2500	0.0005	3.9	. ±5	-	[53]
SU-200-SS	900	Si-acrylic diffuser	305-390	75	Self generating	<1	1	0.1	10	. ±5	±0.05	[54]
PMA1110	300	Si-metal	320-400	60	12	-	25	0.001	200	±5	-	[55]
ML8511	18	Si	280-390	45	10	1	130	0.08	15	±5	±0.1	[56]
Sanseviera cylindrica	7	Plant	350-400	45	Self generating	60k	8.3	0.1	2.6	±10	±4	This work

between the zero condition considered as the absence of UV radiation and the level of UV-A radiation. It includes the uncertainty and the mean value for each considered point. The study highlights a sensitivity of about 8.3 mV/mW/cm^2 and a resolution of about 0.1 mW/cm^2. Furthermore, in terms of lifetime, the living sensor worked for about a year while maintaining the characteristics mentioned, the maximum standard deviation corresponds to about 0.9 mV. In order to compare the performance achieved by the living sensor, with commercial devices, Table II presents the main characteristics of such devices, including price, fabrication process, spectral response, angle of view, power consumption, response time, as well as sensitivity, resolution, range of measurement, accuracy, and thermal drift for each one.

The slope identifies the sensitivity of the living sensor. The following equation describes the response of the device:

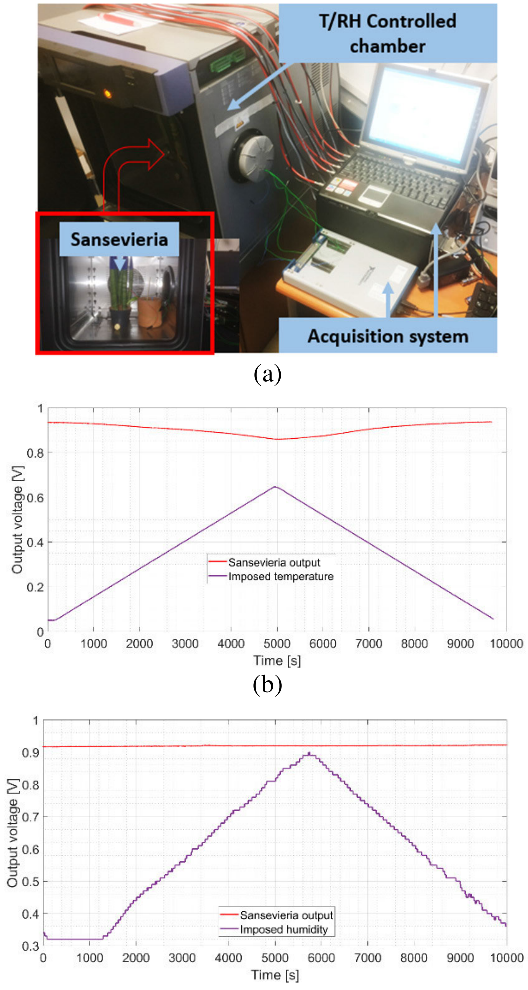
$$V_o = S \cdot I - K|_{K=7.8\ \text{mV}} \tag{1}$$

where V_o is the output voltage, S represents the sensitivity of the device, I is the radiation amplitude of the measurand, and K is a constant value experimentally estimated.

D. Influence Analysis

In order to validate the potentialities of the living sensor characterized in the previous section, particular attention will be given to influences, which could affect the performance of the entire system. For this reason, it is important to study possible signals and quantities which could affect the output voltage of the device, such as the injection of unwanted influences and unrelated environmental signals into the system. Particular emphasis was given to studying hysteretic effects by increasing and decreasing the physical quantities under analysis.

Fig. 11 shows the influence study of the *Sansevieria cylindrica* on temperature variation and relative humidity, which represent two physical quantities found in several application fields. The influence analysis was conducted by using a thermal/relative humidity-controlled chamber, ESPEC Corporation, model SH-242 [as shown in Fig. 11(a)]. The temperature was varied considering the values 5 °C–20 °C–35 °C–50 °C–65 °C and reverse. Each step



(a)

(b)

(c)

Fig. 11. Measurement system used for the influence analysis. (a) Inset highlights the localization of the plant inside the temperature/relative humidity (T/RH) chamber. Influence analysis in terms of (b) temperature, considering the range 5°–65° and reverse and (c) relative humidity, considering a range 30%–90% and inverse step.

of temperature was maintained for 20 min in presence of a constant relative humidity of 50%. Regarding the relative humidity, the values 30%–45%–60%–75%–90% were considered as an inverse step. Each point was maintained for 20 min with a constant temperature value of 20 °C. Considering the temperature study, a voltage of 0.932 V was detected at 5 °C, and an output voltage of about 0.860 V was measured at 65 °C. During the analysis in terms of relative humidity, an output voltage of about 0.917 V was observed at 30%, and a value of about 0.919 V was measured at 90%. The results show an intriguing insensitivity to both parameters with a maximum variation of about 2 mV for a corresponding relative humidity variation in the considered range. Temperature influences the living sensor with a variation of the output voltage of about 70 mV considering the range between 5 °C and 65 °C and a variation of about 30 mV in correspondence of one of about 45 °C. It is worth noting that, considering indoor applications and confined environments, the temperature range that could alter the performance presented in the previous section can be considered out of interest.

IV. CONCLUSION

In this work, a sensor based on a Sansevieria plant was proposed to measure UV-A radiation by using the soil, the plant, and the metabolic processes involved in such organisms. This solution goes beyond classical silicon-based approaches which imply CO_2 emissions during manufacturing and non-biodegradability and toxicity at the dissemination or end of life. It is also able to absorb and reduce the amount of carbon dioxide already present in the environment through natural photosynthetic processes. The living sensor was studied starting from the working principle together with its chemo-electrical transduction principle and through a metrological characterization which includes a calibration diagram, performance estimation, influence analysis, and capability to measure radiation in the bandwidth of 350–400 nm. The results highlighted the suitability of the Sansevieria, which presents a sensitivity of about 8.3 mV/mW/cm^2, a resolution of about 0.1 mW/cm^2, and a range of measurement up to 2.6 mW/cm^2. Furthermore, a maximum variation of about 2 mV was detected for a variation of relative humidity in the range of 30%–90% and a variation of the output voltage of about 30 mV in correspondence of one of about 45 °C. Results evince the possibility to use the sensor as a green self-generating and battery-less device based on the modification of the metabolic processes present in the living system as a function of the measurand. Furthermore, the device presents the prerogative of being simple, low-cost, nontoxic, biodegradable, environmentally friendly, and mimetic. Table III synthetizes the features of the living sensor. It is worth noting that all the aforementioned features are interesting for the realization of a new class of green sensors and focusing the attention on the feasibility of this method for practical purposes, it arouses interest in various fields such as smart agriculture, agriculture 4.0, cultural heritage, and mimetic applications (i.e., UV-A measurement for plant health, plant growth, and UV-A level applied to paintings and artworks) with the goal of achieving environmentally friendly solutions. The work is in progress, in order to improve the work here proposed, with a statistical analysis and with procedures (i.e., vegetative reproduction and vegetative multiplication process [57]) in order to manufacture, for fixed parameters characteristics, the living sensor. Future studies include polymeric contacts, equivalent electrical circuits, and dynamical modeling of the *Sansevieria cylindrica* and soil.

TABLE III
FEATURES OF THE *Sansevieria Cylindrica* USED AS LIVING SENSOR

Parameter	*Sansevieria cylindrica*
Range of measurement	up to 2.6 mW/cm^2
Sensitivity	8.3 mV/mW/cm^2
Resolution	0.10 mW/cm^2
Growth characteristic	~1 cm/year
Influences humidity	~2 mV @ ΔRH~30-90% RH
Influences temperature	~30 mV @ΔT~45 °C
Irrigation features	~1 time/month
Electrodes characteristics/invasiveness	Low invasiveness with Cu/Zn electrodes inside the soil
“Natural” sensitivity range	350-400 nm

ACKNOWLEDGMENT

The authors would like to thank Dr. Emanuele Di Miceli for his support during the experimental characterization.

REFERENCES

[1] O. Kanoun and H. R. Trankler, “Sensor technology advances and future trends,” *IEEE Trans. Instrum. Meas.*, vol. 53, no. 6, pp. 1497–1501, Dec. 2004.

[2] C. Trigona, S. Graziani, and S. Baglio, “Changes in sensors technologies during the last ten years: Evolution or revolution?” *IEEE Instrum. Meas. Mag.*, vol. 23, no. 6, pp. 18–22, Sep. 2020.

[3] I. Zambon, M. Cecchini, G. Egidi, M. G. Saporito, and A. Colantoni, “Revolution 4.0: Industry vs. agriculture in a future development for SMEs,” *Processes*, vol. 7, no. 1, p. 36, Jan. 2019.

[4] H. Veendrick, “The electronics (R) evolution,” in *Bits on Chips*. Cham, Switzerland: Springer, 2019, pp. 3–17.

[5] E. G. Hertwich et al., “Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—A review,” *Environ. Res. Lett.*, vol. 14, no. 4, Apr. 2019, Art. no. 043004.

[6] Accessed: May 2, 2023. [Online]. Available: https://www.cnbc.com/2021/11/03/tsmc-samsung-and-intel-have-a-huge-carbon-footprint.html

[7] N. Tanimura et al., “Estimation of greenhouse gas emissions in micro-fabrication of MEMS devices,” in *Design for Innovative Value Towards a Sustainable Society*. Dordrecht: Springer, 2012, pp. 874–876.

[8] G. Saevarsdottir, T. Magnusson, and H. Kvande, “Reducing the carbon footprint: Primary production of aluminum and silicon with changing energy systems,” *J. Sustain. Metall.*, vol. 7, no. 3, pp. 848–857, 2021.

[9] E. S. Hosseini, S. Dervin, P. Ganguly, and R. Dahiya, “Biodegradable materials for sustainable health monitoring devices,” *ACS Appl. Bio Mater.*, vol. 4, no. 1, pp. 163–194, 2020.

[10] S. Nagano et al., “Environment friendly MEMS fabrication: Proposal of new D-RIE process gases for reduction of green house effect,” in *Proc. IEEE 20th Int. Conf. Micro Electro Mech. Syst. (MEMS)*, Jan. 2007, pp. 341–344.

[11] S. Amaya and S. Sugiyama, “Development of MEMS using biodegradable polymer material,” in *Proc. Transducers Eurosensors pp. 17th Int. Conf. Solid-State Sensors, Actuat. Microsystems*, 2013, pp. 1322–1325.

[12] K. W. Meereboer, M. Misra, and A. K. Mohanty, “Review of recent advances in the biodegradability of polyhydroxyalkanoate (PHA) bioplastics and their composites,” *Green Chem.*, vol. 22, no. 17, pp. 5519–5558, 2020.

[13] R. A. Ilyas et al., “Polylactic acid (PLA) biocomposite: Processing, additive manufacturing and advanced applications,” *Polymers*, vol. 13, no. 8, 1326, 2021.

[14] J. M. Raquez, Y. Habibi, M. Murariu, and P. Dubois, “Polylactide (PLA)-based nanocomposites,” *Prog. Polym. Sci.*, vol. 38, nos. 10–11, pp. 1504–1542, 2013.

[15] D. Nilsson, T. Kugler, P. O. Svensson, and M. Berggren, “An all-organic sensor–transistor based on a novel electrochemical transducer concept printed electrochemical sensors on paper,” *Sens. Actuators B, Chem.*, vol. 6, nos. 2–3, pp. 193–197, 2002.

[16] C. Legnania et al., “Bacterial cellulose membrane as flexible substrate for organic light emitting devices,” *Thin Solid Films*, vol. 517, pp. 1016–1020, Dec. 2008.

[17] G. Di Pasquale, S. Graziani, A. Pollicino, and C. Trigona, “The evolution of ionic polymer metal composites towards greener transducers,” *IEEE Instrum. Meas. Mag.*, vol. 22, no. 5, pp. 30–35, Oct. 2019.

[18] G. Di Pasquale, S. Graziani, A. Pollicino, and C. Trigona, “Performance characterization of a biodegradable deformation sensor based on bacterial cellulose,” *IEEE Trans. Instrum. Meas.*, vol. 69, no. 5, pp. 2561–2569, May 2020.

[19] E. Wawrzynek, C. Baumbauer, and A. C. Arias, “Characterization and comparison of biodegradable printed capacitive humidity sensors,” *Sensors*, vol. 21, no. 19, p. 6557, Sep. 2021.

[20] J. Cheng, L. Wang, J. Huo, and H. Yu, “A novel polycaprolactone-grafted-carbon black nanocomposite-based sensor for detecting solvent vapors,” *J. Appl. Polym. Sci.*, vol. 121, no. 6, pp. 3277–3282, Sep. 2011.

[21] E. Devaux, C. Aubry, C. Campagne, and M. Rochery, “PLA/carbon nanotubes multifilament yarns for relative humidity textile sensor,” *J. Engineered Fibers Fabrics*, vol. 6, no. 3, Sep. 2011, Art. no. 155892501100600.

[22] Y.-H. Wang et al., “A paper-based piezoelectric accelerometer,” *Micromachines*, vol. 9, no. 1, p. 19, Jan. 2018.

[23] E. S. Hosseini, S. Dervin, P. Ganguly, and R. Dahiya, “Biodegradable materials for sustainable health monitoring devices,” *ACS Appl. Bio Mater.*, vol. 4, no. 1, pp. 163–194, Jan. 2021.

[24] C. Trigona, “Feasibility of a soil-based sensor for measurement of temperature,” in *Proc. 17th Int. Multi-Conf. Syst., Signals Devices (SSD)*, 2020, pp. 1155–1158.

[25] A. G. Volkov, *Plant Electrophysiology*. Berlin, Germany: Springer, 2006.

[26] C. Trigona, “Living sensors: The greenest paradigm in instrumentation and measurements,” *IEEE Instrum. Meas. Mag.*, vol. 26, no. 1, pp. 35–41, Feb. 2023.

[27] F. Baluska, *Communication in Plants*. Berlin, Germany: Springer-Verlag, 2006.

[28] V. Sukhov, V. Nerush, L. Orlova, and V. Vodeneev, “Simulation of action potential propagation in plants,” *J. Theor. Biol.*, vol. 291, pp. 47–55, Dec. 2011.

[29] T. A. Cuin, I. Dreyer, and E. Michard, “The role of potassium channels in Arabidopsis thaliana long distance electrical signalling: AKT2 modulates tissue excitability while GORK shapes action potentials,” *Int. J. Mol. Sci.*, vol. 19, no. 4, 926, 2018.

[30] A. G. Volkov, R. D. Lang, and M. I. Volkova-Gugeshashvili, “Electrical signaling in *Aloe vera* induced by localized thermal stress,” *Bioelectrochemistry*, vol. 71, no. 2, pp. 192–197, 2007.

[31] A. Baglieri, A. M. Gueli, M. Pace, S. Pasquale, I. Puglisi, and C. Trigona, “Exploitation of chemo-electrical transduction properties of soil as a function of energy radiation doses and temperature: Preliminary results,” in *Proc. 18th Int. Multi-Conf. Syst., Signals Devices (SSD)*, pp. 1196–1201, 2021.

[32] C. Trigona, G. Napoli, S. Pasquale, I. Puglisi, A. Baglieri, and A. M. Gueli, “A plant-based sensor for UV—A radiation measurements,” in *Proc. IEEE Int. Instrum. Meas. Technol. Conf. (IMTC)*, May 2021, pp. 1–5.

[33] H. T. Aung et al., “Bioactive constituents from the rhizomes of sansevieria cylindrica,” *Records Natural Products*, vol. 14, no. 4, pp. 269–275, Mar. 2020.

[34] L. Taiz, E. Zeiger, I. M. Müller, and A. Murphy, *Plant Physiology and Development*, vol. 6. Sunderland, MA, USA: Sinauer Associates Incorporated, 2015.

[35] D. Ayala-Ruiz, A. C. Atoche, E. Ruiz-Ibarra, E. O. de la Rosa, and J. V. Castillo, “A self-powered PMFC-based wireless sensor node for smart city applications,” *Wireless Commun. Mobile Comput.*, vol. 2019, pp. 1–10, Jun. 2019.

[36] B. Liu, H. Liu, D. Zhong, and C. Lin, “Searching for a photocycle of the cryptochrome photoreceptors,” *Current Opinion Plant Biol.*, vol. 13, no. 5, pp. 578–586, Oct. 2010.

[37] R. Rinnan, C. Gehrke, and A. Michelsen, “Two mire species respond differently to enhanced ultraviolet-B radiation: Effects on biomass allocation and root exudation,” *New Phytologist*, vol. 169, no. 4, pp. 809–818, Feb. 2006.

[38] J. Lin, F. He, G. Owens, and Z. Chen, “How do phytogenic iron oxide nanoparticles drive redox reactions to reduce cadmium availability in a flooded paddy soil?” *J. Hazardous Mater.*, vol. 403, Feb. 2021, Art. no. 123736.

[39] D. Zhang, H. Dang, Z. Li, and C. Zhang, “Redox characteristics of humins and their coupling with potential PCB dechlorinators in southern Yellow Sea sediments,” *Environ. Pollut.*, vol. 252, pp. 296–304, Sep. 2019.

[40] V. Vranova, K. Rejsek, K. R. Skene, D. Janous, and P. Formanek, “Methods of collection of plant root exudates in relation to plant metabolism and purpose: A review,” *J. Plant Nutrition Soil Sci.*, vol. 176, no. 2, pp. 175–199, 2013.

[41] H. Le Van and T. Masuda, “Physiological and biochemical studies on aluminum tolerance in pineapple,” *Austral. J. Soil Res.*, vol. 42, no. 6, pp. 699–707, 2004.

[42] K. R. S. Pamintuan, M. A. L. Calma, K. A. D. Feliciano, and K. J. P. D. Lariba, “Potential of bioelectricity generation in plant-microbial fuel cells growing house plants,” *IOP Conf. Earth Environ. Sci.*, vol. 505, no. 1, 2020, Art. no. 012043.

[43] R. C. Ferrari et al., “C_4 and crassulacean acid metabolism within a single leaf: Deciphering key components behind a rare photosynthetic adaptation,” *New Phytologist*, vol. 225, no. 4, pp. 1699–1714, 2020.

[44] R. Ionel, N. Şerban-Pop, L. Mâţiu-Iovan, and V. Ordodi, “Measurement application for UV-C irradiation intensity evaluation,” in *Proc. IEEE 27th Int. Symp. Design Technol. Electron. Packag. (SIITME)*, Oct. 2021, pp. 189–192.

[45] S. Abd-Elmaksoud, J. E. Naranjo, and C. P. Gerba, “Assessment of a portable handheld UV light device for the disinfection of viruses and bacteria in water,” *Food Environ. Virology*, vol. 5, no. 2, pp. 87–90, 2013.

[46] J. F. Sánchez-Pérez, D. Vicente-Agullo, M. Barberá, E. Castro-Rodríguez, and M. Cánovas, “Relationship between ultraviolet index (UVI) and first-, second- and third-degree sunburn using the Probit methodology,” *Sci. Rep.*, vol. 9, no. 1, pp. 733–746, 2019.

[47] Accessed: May 2, 2023. [Online]. Available: https://apps.who.int/iris/handle/10665/42459

[48] M. Caswell, “The kinetics of the tanning response to tanning bed exposures,” *Photodermatology, Photoimmunology Photomedicine*, vol. 16, no. 1, pp. 10–14, 2020.

[49] M. Zayat, P. Garcia-Parejo, and D. Levy, “Preventing UV-light damage of light sensitive materials using a highly protective UV-absorbing coating,” *Chem. Soc. Rev.*, vol. 36, no. 8, pp. 1270–1281, 2007.

[50] Accessed: May 2, 2023. [Online]. Available: https://www.skyeinstruments.info/index_htm_files/uva-dts-v1a.pdf

[51] Accessed: May 2, 2023. [Online]. Available: https://www.rikasensor.com/rk200-07-uv-radiation-sensor.html

[52] Accessed: May 2, 2023. [Online]. Available: http://www.geni-uv.com/download/products/GUVA-S12SD.pdf

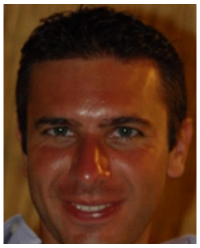
[53] Accessed: May 2, 2023. [Online]. Available: https://www.vernier.com/files/manuals/uva-bta/uva-bta.pdf

[54] Accessed: May 2, 2023. [Online]. Available: https://www.apogeeinstruments.com/content/SU-200.pdf

[55] Accessed: May 2, 2023. [Online]. Available: https://solarlight.com/product/uva-sensor-pma1110/

[56] Accessed: May 2, 2023. [Online]. Available: https://media.digikey.com/pdf/Data%20Sheets/Rohm%20PDFs/ML8511_3-8-13.pdf

[57] R. V. Ivannikov and O. K. Khejlyk, “Vegetative reproduction of Sansevieria cylindrica Boj. (Dracaenaceae Salisb.) in conditions of hothouse culture and culture in vitro,” *Plant Introduction*, vol. 31, pp. 60–65, Sep. 2006.



Carlo Trigona (Member, IEEE) received the M.S. degree (cum laude) in automation engineering and control of complex systems and the Ph.D. degree in electronic, automation, and control of complex systems from the University of Catania, Catania, Italy, in 2006 and 2010, respectively.

From 2010 to 2011, he worked as a Post-Doctoral Researcher and a Lecturer at the Laboratoire d'Informatique, de Robotique et de Microélectronique de Montpellier (LIRMM), University Montpellier II, Montpellier, France; from 2011 to 2017, as a Post-Doctoral Researcher and a Lecturer at the Dipartimento di Ingegneria Elettrica, Elettronica e Informatica (DIEEI), University of Catania; and from 2017 to 2018, as a Post-Doctoral Researcher at the Chemnitz University of Technology, Chemnitz, Germany. From 2018 to 2020, he worked as an Assistant Professor of electronic instrumentation and measurements at the DIEEI, University of Catania, where he worked as a tenure-track Professor of electronic instrumentation and measurements from 2020 to 2023. He is currently an Associate Professor of electronic instrumentations and measurements at the DIEEI, University of Catania. He is involved in several national and international academic and engineering projects as a coordinator and a partner. In addition, he contributes to the Instrumentation and Measurement Community with several activities also including being an editor and a reviewer for several prestigious journals since 2006. Regarding his research activity, he is the coauthor of more than 200 scientific publications, with more than 2000 total citations, which include chapters in books, articles in international journals, and proceedings of international conferences and patents. His research interests include sensors, transducers, micro electro-mechanical systems (MEMS), nano electro-mechanical systems (NEMS), fluxgate magnetometers, energy harvesting, green, biodegradable, and sensors and transducers based on living organisms.

Prof. Trigona received several awards for his research activity in 2007, including the 2020 IEEE I&M Outstanding Young Engineer Award for his outstanding contribution to the advancement of the I&M concept in sensors and transducers for energy harvesting.

Ivana Puglisi is currently an Associate Professor in agricultural chemistry at the Department of Agriculture, Food and Environment (Di3A), University of Catania, Catania, Italy. She has published over 50 articles in an international indexed journal. She is involved in several international, national, and regional research projects. Her research interests include the effect of natural compounds on soil and plant biological activity and the investigation of the primary and secondary metabolism of plant species.

Andrea Baglieri is currently an Associate Professor in agricultural chemistry at the Department of Agriculture, Food and Environment (Di3A), University of Catania, Catania, Italy. He is the President of the degree course in agricultural sciences and technologies. He has published over 60 articles in an international indexed journal. He is involved in several international, national, and regional research projects. His research interests include the reuse of waste biomass in agriculture, studies about the organic matter and humic fractions of the soil, and studies about plant and soil biochemistry.

Dr. Baglieri received the Training Award from the International Humic Substances Society (IHSS).

Anna Maria Gueli received the master's degree (cum laude) in physics from the University of Catania, Catania, Italy, in 1993, discussing a thesis in archaeometry related to the experimental research performed during the Erasmus Project at the University of Bordeaux, Bordeaux, France, the D.E.S.S. degree (Hons.) in physical methods in archeology and museography from the University of Bordeaux, in 1994, and the Ph.D. degree in physics from the University of Catania in 1999. Her Ph.D. dissertation was titled, "Radiation Dosimetry", mainly focused on archeological dating.

She is an Associate Professor in applied physics at the University of Catania and the Head of Physics for Dating Diagnostics Dosimetry Research and Applications (PH3DRA) Laboratories, included in the European Research Infrastructure for Heritage Science through the INFN Cultural Heritage Network (CHNet). Her research mainly concerns the dating of archaeomaterials through stimulated luminescence (TL&OSL) and analytical techniques in art conservation. These last include interdisciplinary approaches to microclimate monitoring and applied colorimetry starting from the optical properties of materials. She obtained a post-doctoral scholarship from CNR and a research grant from the University of Catania. She was a Chercheur Associé from the European Program GRUNDTVIG Adult Education Program from 1999 to 2003 and a Professeur Invitée à temps plein from the University of Bordeaux from 2007 to 2008. She coordinated the activities of Italian researchers within the European Research Group GdRE-TCA "Ceramic Building Materials and New Dating Methods."

Dr. Gueli was an elected member of the Executive Council of the Italian Association of Archaeometry (AIAr) covering the role of General Secretary from 2008 to 2014 and a Treasurer from 2009 to 2011. She is a member of the Color Group of the Italian Color Association, she has been a member of both the Scientific and the Editorial Committees since 2008. She is the Catania's University Delegate at the Permanent Thematic Working Group of the Regional Strategy of the Innovation for the Intelligent Specialization in the area of tourism, cultural heritage, and culture and the National Technological Cluster Project Technological Innovation in Cultural Heritage (TICHE).

Open Access funding provided by 'Università degli Studi di Catania' within the CRUI CARE Agreement