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Measurement of Visible Radiation through a *Sansevieria cylindrica*-Based "Living Sensor"

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Abstract: This research activity regards the development of a sensor based on a *Sansevieria cylindrica* plant for the measurement of visible radiation. The proposed solution, based on the adoption of a soil-plant system as a chemo-electrical transducer, goes beyond "classical" silicon-based approaches that are not biodegradable nor eco-friendly and that produce CO_2 from the production step to the disposal phase. It is worth noting that no toxicity can be associated with plants and, due to the natural process of photosynthesis, these systems, used as living sensors, are even able to absorb carbon dioxide from the environment. The working principle of the proposed device based on the metabolic processes of the natural organisms present in the living system, soil and plant, as a function of visible radiation will be presented here. Particular emphasis will be also given to the analysis of the visible radiation spectrum, the metrological characterization, the performance of the device, and the analyses in terms of insensitivity to other external physical quantities. The obtained results evince the suitability of the proposed device which presents the prerogative of being environmentally friendly, self-generating, battery-less, simple, mimetic, low-cost, non-toxic, and biodegradable. The aforementioned features pave the road for a disruptive technological approach for an ecological transition which can impact the variegated applied field, including in the security, cultural heritage, smart home, and smart agriculture aspects.

Keywords: living sensor; *Sansevieria cylindrica*; soil–plant system; light radiation measurements; environmentally friendly device; ecological transition

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1. Introduction

The extensive use of natural resources and the adoption of industrial processes and fabrication procedures have led to an increase of greenhouse gases and emissions in the atmosphere, causing global climate change [1–3]. Terms such as net-zero carbon dioxide emissions, carbon-neutral, and climate-neutral are used to describe a global target which regards carbon offsetting or the elimination of emissions from society [4,5]. This transition regards various aspects, fields, and scientific disciplines in the applied science [6]. Focusing attention on microelectronic devices, it must be observed that these technological solutions require vast amounts of power during the production process, such as the melting/purification of raw silicon, diffusion furnaces, plasma-etching machines, material deposition onto Si-wafers, etc. [7–9].

These days, the common goal is the development of micro-scale devices (such as MEMS or NEMS systems) capable of being used as sensors, transducers, operation circuits, and data decoding or transmission devices [10–12] for variegated applications ranging from industry to agriculture, cultural heritage, and security [13]. Such electronic systems have low costs, so they are massively produced by industries. Certainly, the budget of an electronic device should also account for the impact on the environment when such devices are produced and, even more, when such devices must be disposed [14].

It should be considered that silicon-based solutions cause environmental pollution with CO_2 emissions during manufacturing, and problems of non-biodegradability and toxicity at the dissemination or end-of-life step [15]. The CO_2 issue arouses particular interest considering that the quantities present in the air may also be harmful to the environment and to humans. Furthermore, e-waste production and the disposal of exhausted electronics after their end of life is a big environmental issue and the contribution of emissions also strongly includes foundries and the disposal processes of silicon-based devices [16]. This amount of produced pollutants exceeds any other industrial production, including the giant automotive and car production. From the perspective of reducing carbon emissions and the energy budget during fabrication, several chipmakers, semiconductor industries, and silicon foundries started various actions to ensure a massive reduction of emissions [17]. Considering the difficulty of sustainable approaches in conventional electronics, the trend is in the direction of non-silicon electronic components of circuits, sensors, and transducers [18]. A clear tendency is shown in the literature to use polymers or biomaterials to fabricate devices, with the goal that they will be environmentally friendly [19,20]. Using some of these materials, it is possible to implement organic light-emitting diodes (OLEDs), organic field-effect transistors (OFETs), both the n-type and the p-type; and transducers and converters based on polymeric substrates such as polyethylene terephthalate (PET) or polycarbonate (PC) [21,22]. The evolution of green sensors can be found in [18], where the authors present solutions capable of implementing the next generation of green electroactive polymers for active substrate and motion transducers. Such materials, as described in the case of sensors, make organic electronics greener, although small amounts of materials do not make it totally green. Such solutions, both at the sensor and electronic components level, lead to a CO_2 emission equal to almost zero and a biodegradability < 100%. The objective of this paper is to go beyond this technological limit and paradigm, by developing not only a sensor that is 100% biodegradable, with no CO_2 emissions during the production, considering the absence of manufacture and foundry processes, but also a device that is able to absorb the CO_2 already present in the environment, through its natural photosynthetic processes. The idea is to adopt a soil–plant system as a "living" sensor having the following prerogatives: self-generating, eco-friendly, non-toxic, with zero CO_2 emission, and biodegradable. It is worth noting that this latter feature is guaranteed considering that the system is part of nature; it is fully biodegradable and can be "naturally" absorbed (i.e., at the end of life). Full biodegradability can also be achieved through the adoption of suitable electrodes (i.e., bio-polymers). The main characteristics regard the possibility of using the "natural" sensing properties of plants and intrinsic chemo-electrical transductions to obtain an output voltage as a function of the physical quantity of interest.

The choice of plant is of particular interest and represents a crucial selection, to consider a living sensor sensitive only to a specific measurand and not to other physical quantities.

In this context, the sensing characteristics of plants have been widely studied in the context of plant biology and various studies have been conducted in the field of electrophysiology [23]. In fact, after the first recorded action potential in an insectivorous plant [24], research in this area has increased dramatically and it is still ongoing, with great actuality and scientific relevance. It is worth noting that, still, many aspects of plant responses are not sufficiently well-elaborated and understood. Plant electrostimulations, response to external physical quantities and stress, intracellular measurements, and depolarizing currents and fluxes (i.e., Cl^- and Ca^{2+}) are fundamental points which involve the electrophysiology of plants, vegetal organisms, and the study of health and applied stress in plants through electrical signals generated by the plant itself [25–27]. It thus becomes apparent how plants are able to generate electrical responses as a function of external physical quantities.

For example, in [28], the authors propose a plant, genus *mytillocactus*, with electrodes implanted inside it in order to demonstrate that, with electrodes, it was possible to harvest the glucose and O_2 produced during photosynthesis to generate energy. The authors investigated the current responses upon the illumination/darkness cycles. Both the evolutions of the O_2 electroreduction current and of glucose electro-oxidation current were measured demonstrating the maximum electrical response in the order of 0.5 μA.

The choice of the living organism in fact is of primary importance, and, in order to be considered a sensor, the following characteristics are required: the definition of performance, features, robustness, "natural" insensitivity, ability to measure only one physical quantity of interest and be insensitive to the others, metrological characteristics and characterization also as a function of influence and interference quantities, hysteresis, nonlinear behavior, etc. [23,27,29]. It should also be noted that the aspect of electrical contacts is crucial since a living sensor should be able to work and operate for a long time without damaging the plant with directly implanted contacts [30]. For this reason, an electrical decoupling mechanism represents an essential characteristic to be accounted for, in order to implement a living sensor [31]. Obviously, the choice of the soil-plant system is also crucial for finding plants that require a small amount of water and restrained growth. Obviously, the choice of plant is not trivial and requires a metrological study in order to have a system that not only generates electrical signals but is able to generate a voltage, without the adoption of batteries, with the amplitude corresponding to the measurand.

In this context, the literature presents few papers on soil and soil–plant systems used as living sensors: for example, in [32], the author demonstrated with a characterization the possibility of using soil as a self-generating sensor for temperature measurements obtaining, by using two implanted electrodes in the soil, a sensitivity of about -8.96×10^{-4} V/°C and a resolution of about 7 °C with an operative range of 0–50 °C. Various studies have subsequently been carried out in order to analyze and investigate the transduction principle by varying the bacteria and the enzymatic activities driven by the X-ray source and temperature variations as a function of various observation time [33].

In ref. [34], the authors presented a soil–plant system in order to implement a living sensor for the measurement of UV-A band radiation (315–400 nm). A *Dimorphotheca ecklonis* was used as a plant with electrodes placed inside the soil to minimize invasiveness for the plant itself by using the soil as a decoupling component. The metrological characterization was accomplished in order to validate the working principle of the sensor which presented a sensitivity of about 6.6 mV/mW/cm^2 and a resolution of about 0.13 mW/cm^2 with an operative range reaching up to 0.6 mW/cm^2. This manuscript improves the state of the art, presenting a sensor based on *Sanseviera cylindrica* to measure the intensity of visible light (Vis-light). To the best of the authors' knowledge, this is the first demonstration of a living sensor realized by using a soil–plant system based on *Sanseviera cylindrica* with electrodes installed in the soil with the following intriguing characteristics: self-generating, simple, low-cost, non-toxic, biodegradable, and environmentally friendly. All the aforementioned features arouse interest in order to contribute to decarbonization, due to their innovative nature that goes beyond the paradigm of classic silicon-based sensors.

It is worth noting that, due to its mimetic property, the proposed solution is suitable in various fields, with a focus on indoor and outdoor applications for cultural heritage, security, smart home, smart city, and smart agriculture. The obtained materials and methods are presented in Section 2 together with the working principle and the characterization setup. Section 3 presents the results, and, in particular, it includes the analysis and spatial distribution of the applied illuminance, the selectivity achievement of the proposed living sensor, and the metrological characterization with the features of the device. The concluding remarks are given in Section 4.

2. Materials and Methods

Sansevieria cylindrica, commonly named *Sansevieria*, belonging to the genus *Dracaena* (family *Asparagaceae*), is also known as *Dracaena angolensis*, and it is a *Crassulaceae* plant originating from subtropical African regions [35]. During its growing season, *Sansevieria* requires moderate amount of water, if given the correct illumination, being a drought-tolerant species. In general, *Crassulaceae* are drought-resistant plants, in that all their tissues may be considered water-storing tissues, characterized by a typical carbon fixation pathway, well known as crassulacean acid metabolism (CAM), which evolved in plants which have adapted to arid conditions as they are able to photosynthesize during the day, keeping closed their stomata and exchanging gases only during the night [36]. *Sansevieria cylindrica* was the plant used in this study about the measurement of Vis-light. *Sansevieria asparagaceae* was also implemented and adapted as a plant microbial fuel cell (PMFC) power cell with an energy harvester circuit to supply direct current energy output power to the sensor nodes to collect and monitor the information for environmental protection, urban planning, and risk prevention [37]. Therefore, the choice of this plant is due to its characteristics as care system, which allows easy cultivation, both indoors and outdoors. Moreover, for its physiological characteristics, *Sansevieria cylindrica* may be a suitable prototype sensor for monitoring several indoor environmental changes such as Vis-light intensity.

Focusing our attention on the proposed approach, recently, *Dimorphotheca ecklonis* was successfully used as "living sensor" for UV-A radiation measurements, and the mechanism hypothesis was linked to the photoexcitation of cryptochromes by processes involving electron transfer and flavin reduction [34,38].

It is well-known that alteration in the influx and/or the efflux of metabolites from the epigeal part of the plant to the root tip can have cascading effects on the root system architecture, and hence on root rhizodeposition [39], thus leading to a change in the net efflux of root exudates in the rhizosphere, which is the soil fraction directly influenced by roots and associated with soil micro-organisms [40]. Root rhizodeposition may strongly influence the physiochemical properties of the rhizosphere, putatively inducing a change in the soil redox potential [41]. The compounds in root rhizodeposition, especially sugars and organic acids, may differ depending on the type of plant metabolism [42]. The qualitative composition of root exudates in CAM plants showed the occurrence of high amounts of succinate, malate, and citrate, organic acids which can affect the electrochemical properties in the rhizosphere [43,44]. Moreover, using three different plant prototypes with different metabolisms (C3, C4, and CAM) to determine the output power of the PMFCs, CAM plant registered the highest maximum power density among plants, at 30.39 mW/m^2 [45]. CAM plants, as they are drought-resistant, are able to generate rhizodeposition even in dry soil conditions [46].

In different environmental light conditions, plants may modulate their primary metabolism by regulating photosynthesis [46]. Plant carbon allocation and distribution in their tissues are regulated by the source–sink dynamics, and soil micro-organisms should also be considered as a strong sink of plant photosynthates, thereby promoting root exudation [46–48].

A hypothesis to explain the obtained results in this study may be linked to the regulation of plant photosynthate flux from the epigeal to the hypogeal part of the plant in response to light modulation, thus inducing root exudate production, which may modify the soil redox potential, and therefore the measurable signal among cathode and anode (Figure 1).

In order to implement the living sensor, its working principle, in accordance with the aforementioned, will be considered and, in particular, the root exudate production changes the soil redox potential at each dry condition, thus determining a measurable signal among cathode and anode depending on Vis-light intensity.

To study and to characterize the sensing system, a suitable experimental setup was conceived. Figure 2 shows its schematization which includes:

- A *Sansevieria cylindrica* having 15 stems for which we assume the shape of a cone with radius and height of about, respectively, 6.5 mm and 30 cm, so a base area of about 132.6 mm^2 is estimated, and a total area of 6257 mm^2 for each stem;
- A visible light source with a spectrum typical of D65 CIE illuminant, composed of 4 neon lamps, each one of 18 W;
- A support system useful for changing the distance between source and plant and, as a consequence, the intensity of the light intensity on living sensor;
- A controlled chamber, ESPEC CORP., model SH-242 used to investigate the influence of temperature and relative humidity on the device response;

- Two electrical contacts of Zn and Cu, placed inside the soil at a depth of 6 cm, 8 cm apart, that represent, respectively, anode and cathode of the device;
- A LabVIEW™ routine to acquire the output voltage coming from the soil–plant system;
- A NI USB-6366 DAQ board with a laptop, adopted to continuously acquire the data;
- MATLAB® processing to elaborate the acquired experimental data.

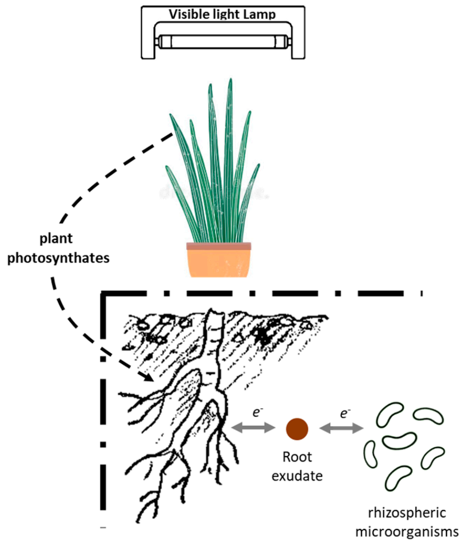
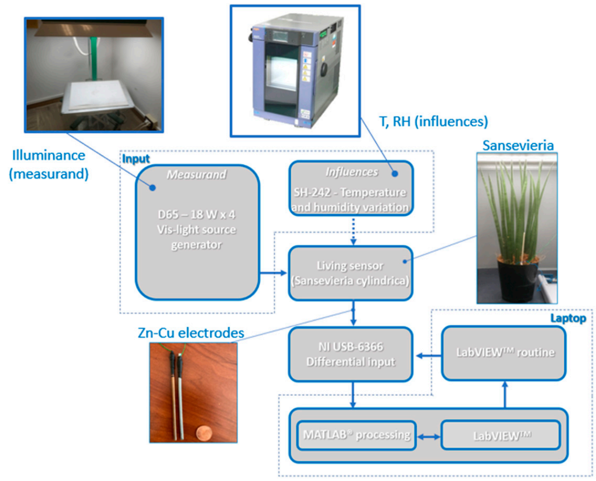
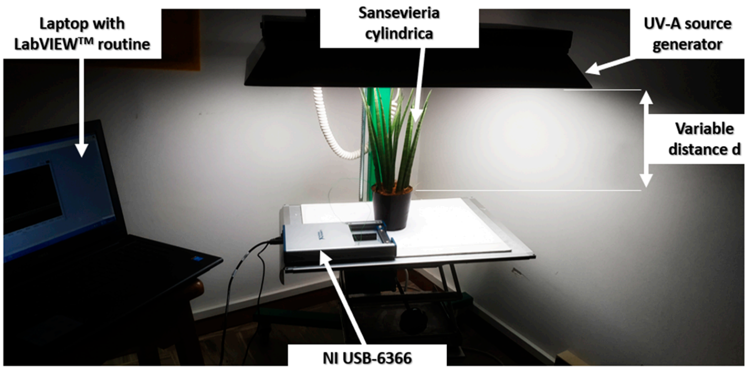


Figure 1. Vis-light radiation detection in *Sansevieria cylindrica*.



(**a**)



(**b**)

Figure 2. Block diagram of the measurement system for the characterization (**a**) and the experimental setup (**b**).

3. Discussion

The experiments were accomplished considering three aspects of measurement campaigns: the first step regards the study of the distribution of Vis-light intensity, in terms of illuminance, as a function of the distance between the light source and the *Sansevieria* living sensor. The second step concerns the study of the selectivity of the living sensor to Vis-light variation and its insensitivity to other physical quantities. It is worth noting that this phase includes the influence analysis of the device. The third phase focuses on metrological characterization to demonstrate the ability of the proposed system to measure the visible radiation incident on the *Sansevieria cylindrica*.

3.1. Analysis and Spatial Distribution of Applied Illuminance

From the perspective to characterize the living sensor based on *Sansevieria cylindrica*, an analysis of the illuminance with spatial distribution studies and the response of the specific measurand adopted during characterization was accomplished. First, the spectral power distribution of the source applied to the *Sansevieria cylindrica* is measured using a Konica Minolta CS-1000 Spectroradiometer (Figure 3).

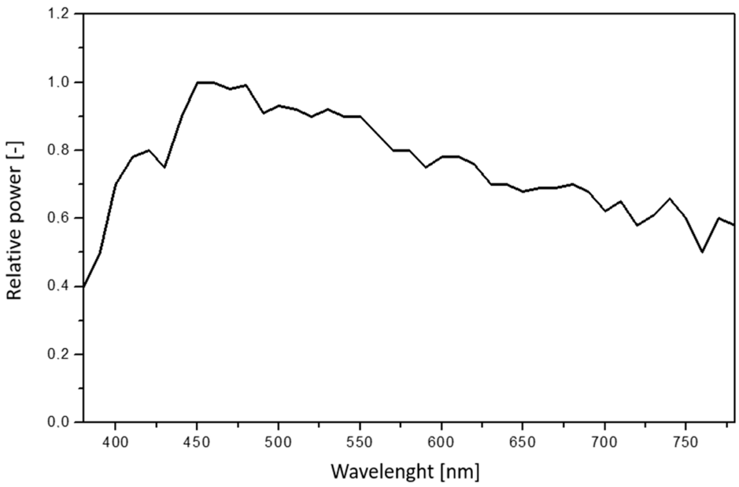


Figure 3. Spectral relative power distribution as a function of wavelength for the light source used.

By varying the distance d between the source and the living sensor, shown in Figure 2b, the illuminance trend with distance shown in Figure 4 was then obtained. This last series of measurements is necessary because the characterization of the sensor was performed at various light intensity levels obtained just by varying the distance between the light source and the plant.

As can be observed, the illuminance shows a decreasing trend with distance in agreement with what is expected. The graph shows the values obtained with an illuminance meter (Konica-Minolta model T-10) in the distance range of 10–60 cm and the fit function that best approximates the experimental data (y = $a + b{\cdot}x^{-2}$).

The analytical trend corresponding to the illuminance I as a function of distance d can be expressed as follows:

$$I(d) = 1727 + 876,162{\cdot}x^{-2} \quad (1)$$

Although the source is not point-like, the experimental data follow the trend as a function of the square of the distance. Moreover, the known term reproduces well the light level corresponding to the ambient background.

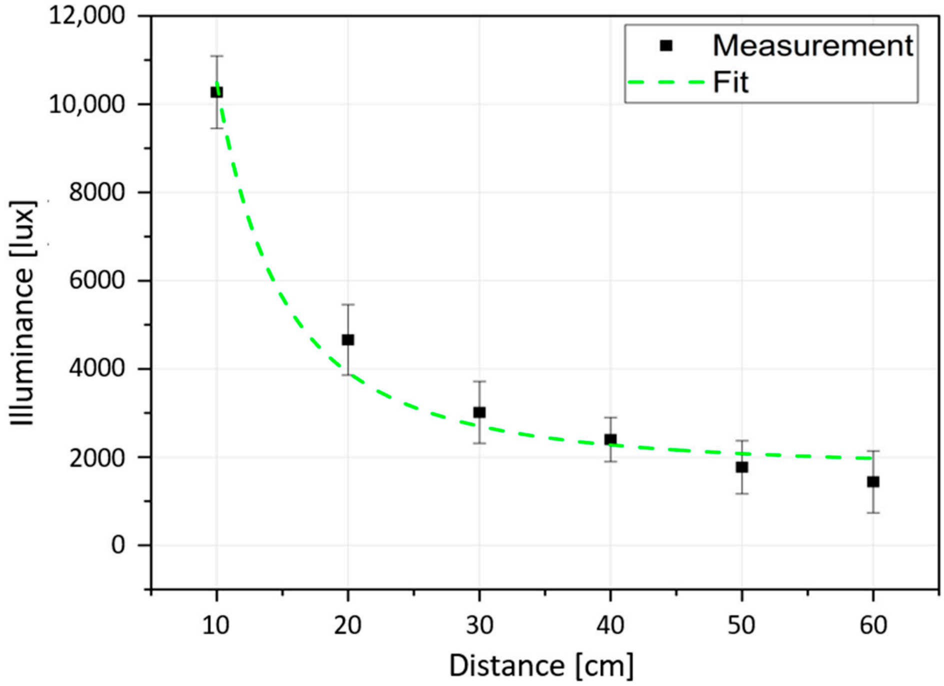


Figure 4. Illuminance level as a function of the distance d from source and detector.

The distribution of illuminance values within the square area with sides of 20 cm, on which the plant is placed during the measurements, is shown in Figure 5 in the form of 3D graphs for six values of distance d, from 10 cm to 60 cm. Each graph represents the illuminance level as a function of the spatial co-ordinates. A decrement of the illuminance level as a function of d is clearly visible. In particular, considering the minimum distance d of 10 cm, a corresponding maximum illuminance level of about 10,270 lux was measured at the center of the spatial grid, while the minimum level was measured at the final part of the grid and corresponds to about 4700 lux. Considering the maximum distance d of 60 cm, the maximum illuminance level decreased to about 1438 lux, while a minimum level of about 1080 lux was observed. Table 1 summarizes the minimum and maximum illuminance values, and the corresponding co-ordinates, measured for each distance.

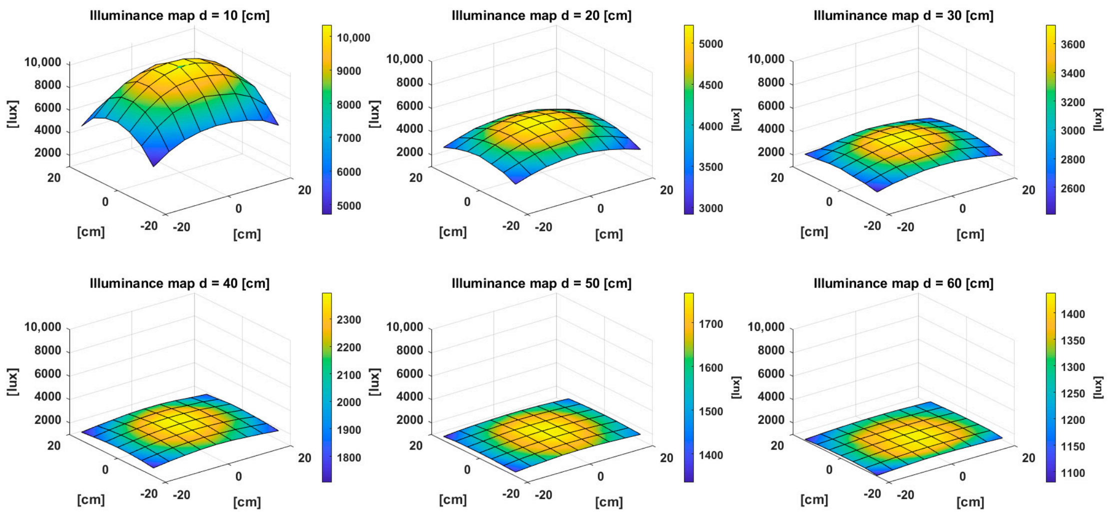


Figure 5. Analysis of the illuminance distribution applied to the *Sansevieria cylindrica* for various distances between source of light and plant.

Table 1. Measured minimum and maximum illuminance values for each distance.

d [cm]	Min [lux] @ (−15 cm, −20 cm)	Max [lux] @ (0 cm, 0 cm)
10	4700	10,270
20	3080	5220
30	2411	3730
40	1722	2395
50	1369	1769
60	1080	1438

3.2. Selectivity Achievement of the Living Sensor

This section is devoted to studying the selectivity of the living sensor in order to investigate physical quantities, different with respect to the Vis-light, which could affect the output voltage and can lead to distortions of the measured value. In fact, the analysis of the influence, external parameters, and signal varying randomly, different with respect to the measurand, which act on the system, arouse interest for the exhaustive characterization of the sensor. Among these factors, the change of temperature and relative humidity has a significant effect on the sensor, affecting directly or indirectly the measurement accuracy and the robustness of the entire system. To study the selectivity of the *Sansevieria cylindrica*, the thermal/relative humidity-controlled chamber, Espec SH-242, presented in Section 2, was used. Figure 6 shows the output voltage coming from the electrodes as a function of the applied temperature inside the chamber and for fixed values of illuminance and relative humidity (50%). The temperature was increased from 5 °C to 65 °C with a step of 10 °C over a period of time of 5000 s. The procedure was pursued by increasing and decreasing the temperature in order to investigate nonlinearities and hysteretic behaviours also related to root exudate production and the consequent modification of the soil redox potential.

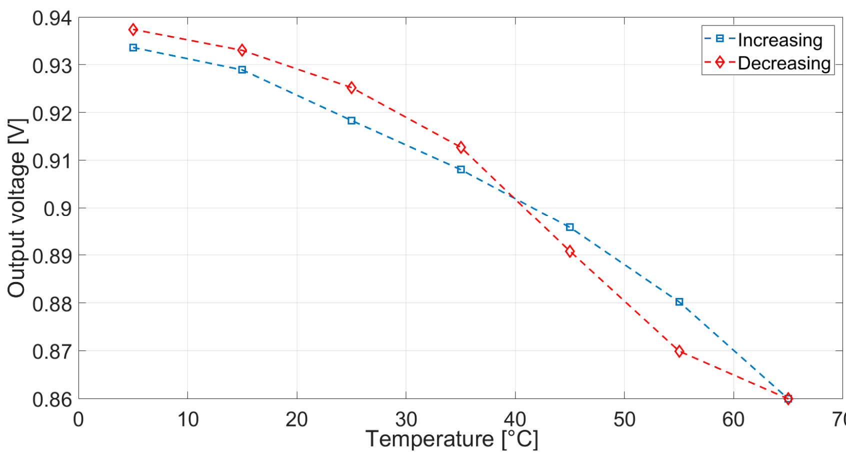


Figure 6. Temperature effects on the output voltage. The graph includes the increment and decrement evolution as a function of the applied influence.

Focusing our attention on the relative humidity variation, Figure 7 shows the output voltage coming from the electrodes as a function of the applied relative humidity inside the chamber and for fixed values of illuminance and temperature (20 °C). The relative humidity was increased from 30% to 90% with a step of 10% over a period of time of 5000 s. As with temperature, the measurements were performed in order to study the effect of hysteresis. Tables 2 and 3 show the effect of temperature and relative humidity, respectively, on the output voltage of the living sensor. The results evince a maximum variation of output voltage, estimated as the difference between the voltage during the increment (V_I) and the voltage during the decrement (V_D), of about 10.3 mV and 2.2 mV for the temperature and relative humidity analysis, respectively. The next section will be devoted to the metrological characterization of the device. Performance considerations and features, also taking into the account the results obtained here, will also be conducted.

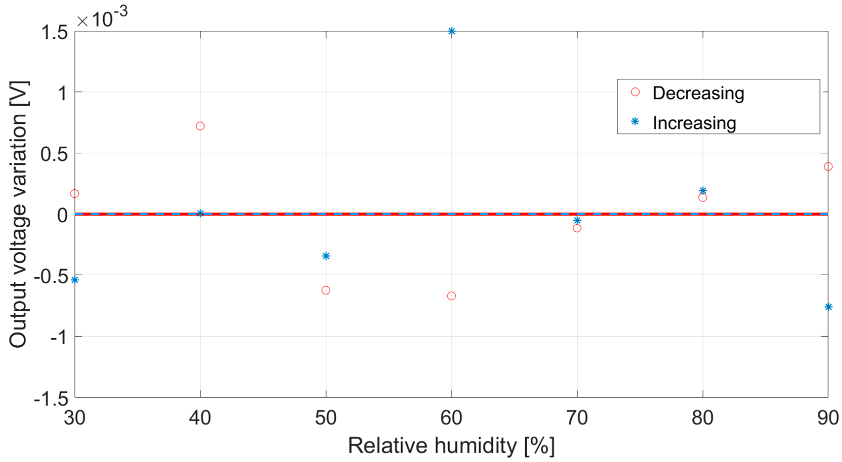


Figure 7. Relative humidity effects on the output voltage; the graph includes the increment and decrement of the influence applied to the plant. The y = 0 line is included as a visual guide.

Table 2. Temperature influence on the output voltage.

T [°C]	V_I [V]	V_D [V]	$\lvert\Delta V\rvert$ [mV]
5	0.9336	0.9374	3.8
15	0.9289	0.9330	4.1
25	0.9183	0.9252	6.9
35	0.9080	0.9127	4.7
45	0.8958	0.8908	5.0
55	0.8802	0.8699	10.3
65	0.8599	0.8599	0

Table 3. Relative humidity influence on the output voltage.

RH [%]	V_I [mV]	V_D [mV]	$\lvert\Delta V\rvert$ [mV]
30	−0.5393	0.1679	0.7
40	0.0071	0.7214	0.7
50	−0.3464	−0.6250	0.3
60	1.5000	−0.6714	2.2
70	−0.0536	−0.1179	0.1
80	0.1929	0.1357	0.1
90	−0.7607	0.3893	1.2

3.3. Metrological Characterization and Discussions

This section focuses on the characterization of the living sensor; in particular, in order to validate the working principle presented in Section 2, the first study regarded the evolution of the output voltage as a function of various distances, d, between the source and the sensor. It is worth noting that Figure 8 shows the response of the *Sansevieria cylindrica* as a function of time for five distances, from 40 cm to 60 cm, which correspond to about 2395 lux to about 1438 lux, respectively. The graph evinces a decrement of the voltage correlated with a decrement of the distance.

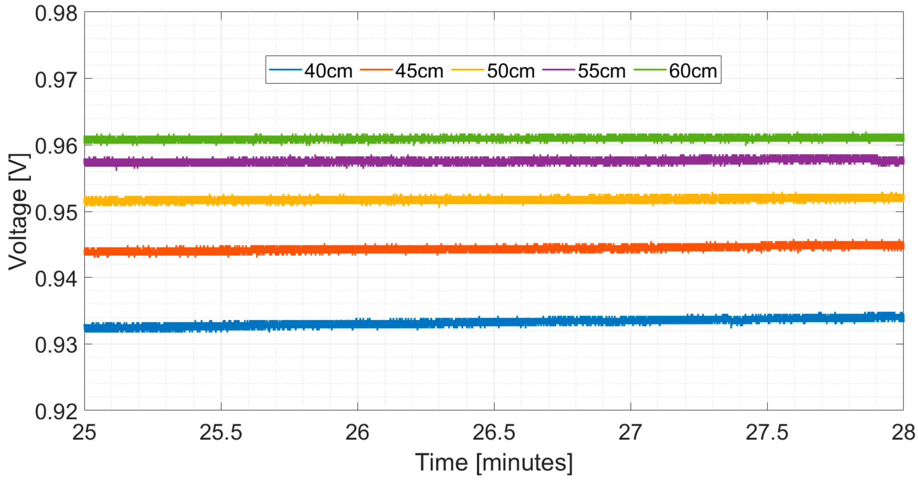


Figure 8. Output voltage across the electrodes as a function of the time considering various distances between plant and Vis-light source.

Figure 9 shows the output voltage as a function of the measurand considering an irradiation level of 1400–2400 lux. The graph includes the mean value of measurements corresponding to each value of irradiance and the linear interpolation. The following transduction function between the measurand (I) and output voltage (V_{out}) can be observed:

$$V_{out} = -2.9 \times 10^{-5} \cdot \text{I} + 1 \quad (2)$$

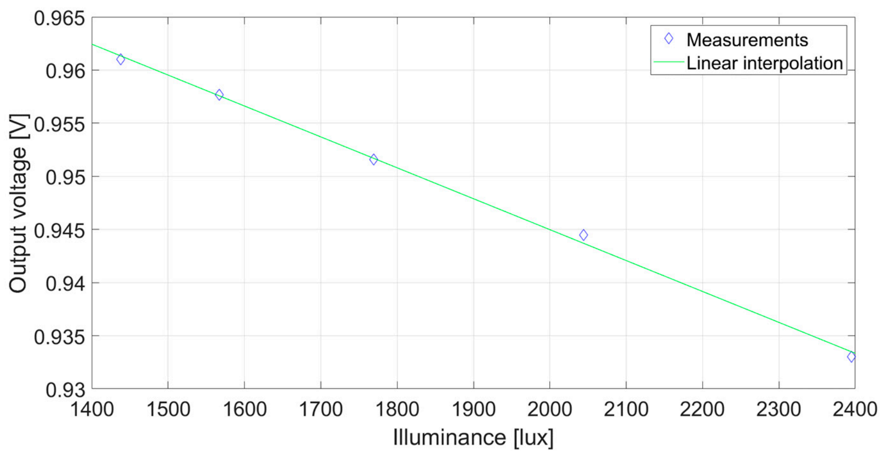


Figure 9. Output voltage as a function of the irradiation level.

Figure 10 shows the calibration diagram of the *Sansevieria cylindrica* as a function of the applied Vis-light. The graph includes the linear interpolation and each point represents the difference between the measurement and the absence of the measurand in terms of the dark level for the living sensor (ΔV_{out}). It includes the uncertainty, expressed as an error bar, and the mean value obtained from 10 repeated measurements of the data of interest. Furthermore, the following sensitivity (S) can be estimated:

$$S = \frac{\Delta V_{out}}{I} = 2.9 \times 10^{-5} \frac{V}{lux} \quad (3)$$

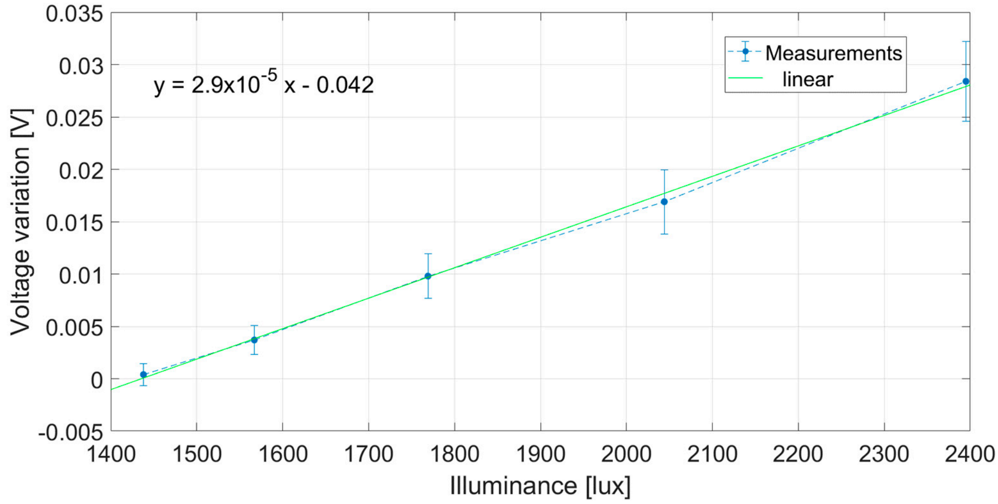


Figure 10. Calibration diagram of the *Sansevieria cylindrica* used as living sensor.

Considering that, during the characterization, a noise level of 3.8 mV was measured, and taking into the account the sensitivity coming from the slope of the transduction function, by inverting the model (3), the resolution of the sensor which corresponds to about 131 lux can be estimated.

It is worth mentioning that, considering the selectivity study presented in the previous section, assuming a temperature working condition of 25 °C and hypothesizing a variation of ambient temperature between 15 °C to 35 °C, an output voltage variation, considering the worst case of the hysteresis presented in Figure 6, of about 10.6 mV (decreasing at 15 °C) and 12.5 mV (increasing at 35 °C) can be observed. These variations could affect the resolution by a factor of about 3.3. This condition could occur for applications such as outdoor sensing for garden monitoring, and the prevention of disease and the upkeep of the health status of other plants, or for possible low-cost, disseminable mimetic devices or measurement systems for smart cities, environmental monitoring, and cultural heritage (i.e., indoor and outdoor microclimate measurements). In fact, in this latter scenario, the European standard, UNI 10829 [49], evinces that the range of operation of the proposed device and its resolution allow us to measure the thresholds in order to preserve the works of arts, both indoors (artificial light) and also outdoors (natural light). Focusing our attention on influences, in the case of controlled environments and indoor areas such as smart homes and museums, the temperature variations are often much lower, leading to improvements in performance and resolution. It should also be noted that the hysteresis detected does not lead to a major deterioration in performance, having measured a maximum voltage variation of 10.3 mV at 55 °C, which represents an implausible temperature for the aforementioned applications. The living sensor also presents an interesting insensitivity to relative humidity, in fact, hypothesizing a variation of ambient relative humidity between 30% to 90%, an output voltage variation, considering the worst case presented in Figure 7, of about 2.1 mV which represents a weak voltage variation and lower with respect to the noise level detected. Therefore, the resolution cannot be affected.

4. Conclusions

In this paper, a living sensor based on a *Sansevieria cylindrica* plant was presented. The main objective was to verify that the plant was sensitive to changes in light intensity on a regular basis and that this was related to the variation in a measurable electrical quantity. The measures performed made it possible to achieve this goal, and it is possible to state that the present paper proposed for the first time in literature a device capable of measuring visible radiation, and the approach pursued here evinces important features such as being environmentally friendly, self-generating, mimetic, battery-less sensor, simple, low-cost, non-toxic, and biodegradable. It is worth noting that the device proposed here also improves the state of the art in terms of greenness. Through its criterion, it is capable of going beyond "classical" silicon-based approaches that are not biodegradable nor eco-friendly and that produce CO_2 from the production step to the disposal phase. Furthermore, no toxicity can be associated with plants and, due to the natural process of photosynthesis, the living sensor is able to absorb carbon dioxide present in the environment. The working principle, together with the transduction mechanism, was presented, as well as the results, in terms of the spatial distribution of applied illuminance; the selectivity achievements and metrological characterization were addressed in order to demonstrate performance and the suitability of the proposed sensor, which can be applied in various fields such as indoor and outdoor monitoring for cultural heritage, smart home, smart agriculture, and smart cities.

The measurements carried out until now showed the validity of the approach and enabled experimental procedures to be developed to verify the limits and potential of the device for the various hypothesized applications.

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