A leaf-mounted capacitance sensor for continuous monitoring of foliar transpiration and solar irradiance as an indicator of plant water status

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Abstract

A leaf-mounted sensor is described, which detects condensing water vapour originating from leaf transpiration, taking advantage of a passive temperature gradient across the sunlit leaf and the underneath sensor plate, and simultaneously monitors incident solar radiation. The simple and low-cost device enables the qualitative assessment of plant water status by comparing the diurnal patterns of leaf transpiration and solar irradiance. A close correlation between condensation and irradiance occurs in conditions of unrestricted water supply, whereas a deviation of their course likely indicates a suboptimal plant water status.

Introduction

Sustainable water management is a major challenge for agriculture in times of diminishing water resources due to climate change and rising demands by an increasing world population. Limited water availability has already become one of the most critical constraints for agriculture in many parts of the world. Given the limited water resources, an increase in agricultural production can only be achieved by optimising irrigation and improving water use efficiency (WUE). For improving WUE, it is crucial to match irrigation timings and volumes with actual plant water needs. However, this requires an accurate knowledge of the water status of plants throughout the growing season.

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Most commonly, modern irrigation scheduling is based on the computation of soil water budgets or the use of soil moisture sensors. The calculation of soil water budgets involves many variables concerning climate, vegetation, and soil (Allen *et al*., 1998). Since typically only part of the needed parameters are known for a given site, the computation of the water budget often requires several assumptions or estimates, which may introduce substantial error over time (Jones, 2008).

Soil moisture sensors are based on different principles of operation (Scanlon *et al*., 2002) and generally provide an output in terms of soil water content or soil water potential. Soil moisture sensors have become increasingly attractive due to advances in electronic data acquisition and wireless communication technology (Cahn and Johnson, 2017; Lloret *et al*., 2021) and are, therefore, frequently used for the irrigation management of various crops. However, soil moisture sensors are of more limited use when dealing with deep-rooting crops, such as perennial woody plants, which may develop roots of up to several meters in depth. Under such circumstances, soil moisture sensors, normally placed in the upper horizons of a soil profile, may not accurately reflect the overall soil water status in the root zone of the plants (Gruber and Schultz, 2005; Wilson *et al*., 2020).

In the endeavour to overcome the disadvantages of soil-based sensors, the development of plant-based sensors for determining plant water status has been a significant focus of research for many decades. Numerous methods and techniques for measuring parameters related to the water status of plants have been proposed over the years, including the determination of stem or leaf water potential, stomatal conductance, sap flow, leaf thickness, leaf temperature, trunk or fruit diameter, and others. Detailed reviews of such plant-based methods have been provided, *e.g.*, by Jones (2004) and, more recently, by Fernández (2017) or Scalisi *et al.* (2018). For an effective and large-scale application in commercial agriculture, an ideal irrigation scheduling system should present several features, including sensitivity, rapid response, adaptability to different crops, reliability, user-friendly operation, the capability of automation, and low cost (Jones, 2008).

Stomatal conductance is a key physiological parameter linked to plant water status, which directly governs leaf transpiration (Fernández, 2017). It is well known that plants react to diminishing soil water reserves by modulating stomatal gas exchange (Buckley, 2019). When foliar transpiration by the plant's canopy exceeds the rate of root water uptake, the plant may, for a certain period, compensate this deficit by contributing water stored in its own tissues to transpiration. This leads to a reduction of the tissues' relative water content and a concomitant decrease of the respective water potentials. Most of the commonly used indicators of plant water status, such as leaf relative water content, leaf and stem water potentials, leaf thickness, stem or fruit diameter, and others, are direct or indirect consequences of the intertwined dynamics of plant transpiration and water uptake (Jones and Higgs, 1979; McBurney, 1992; Levin and Nackley, 2021).

Monitoring leaf transpiration over time in relation to atmospheric evaporative demand could provide useful information about the water status of a plant. Many instruments have been conceived for measuring stomatal conductance or leaf transpiration, but none are suitable for automated, long-term operation under field conditions (Pearcy *et al*., 2000). One of the approaches to detect transpiration flow is to force water vapour to condense on a surface whose temperature is below the dew point of the surrounding atmosphere (Moreshet and Yocum, 1972).

Here we present a low-cost, leaf-mounted sensor that is capable of continuous, real-time monitoring of foliar transpiration by sensing condensing water vapour. The condensation process is driven by a falling temperature gradient which occurs naturally across the sunlit leaf and the underneath sensor plate. The sensor operates on a capacitive principle and also includes a photodiode acting as a light sensor. The continuous, simultaneous determination of incident light and leaf transpiration allows a qualitative evaluation of the plant's water status by comparing the pattern of plant transpiration with the course of solar irradiance as its main driving force (Miner *et al*., 2017). Furthermore, the sensor is resistant to adverse atmospheric conditions and requires very little power, making it well-suited for long-term, continuous operation under field conditions. Potential applications include environmental studies and improved irrigation management of agricultural crops.

Materials and Methods

Sensor design and principle of operation

The proposed device consists of a specially designed printed circuit board (PCB) comprising a circular capacitance sensor and a photodiode. Vapour deposition on the circular sensor plate affects the capacitance measured between two circular, interdigital electrodes. The circular design and rotational symmetry of the sensor makes it less sensitive to orientation than interdigital sensors with rectangular electrodes (Chen and Bowler, 2013). Furthermore, due to its ring-shaped outer frame, the sensing device can easily be fastened on a leaf like a paper clip (Figure 1).

The capacitance-sensing electrodes are formed by circular, concentric copper traces printed on the central plate of the PCB. The sensor electrodes generate an electric field that extends into the adjacent space upon excitation. The sensor penetration depth, which is the depth to which the electric field extends from the sensor plane, is directly correlated to the distance between sensor traces (Chen and Bowler, 2013). For a given sensor geometry, the sensor capacitance depends mainly on the dielectric property of the medium within its electric field. In the case of the presented sensor, the traces and the gap between traces have a width of 0.127 mm, which was the smallest size available for production by a commercial PCB manufacturer. This tight interdigital spacing was chosen to achieve the smallest possible penetration depth, with the objective of detecting mainly vapour deposited on the sensor surface rather than changes in the dielectric properties of the nearby leaf tissues. Moreover, a narrow spacing of the electrode traces increases the sensor's capacitance for a given area. The sensors used for the tests described here had a diameter of the sensing area of 13 or 20 mm and were manufactured with 1 mm thick FR4-Standard Tg 130-140C type of material, covered with a white solder mask.

A BPW34 photodiode (Vishay Semiconductors, Malvern, PA, USA) was added to the sensing device to monitor incident sunlight as the most critical driving factor for leaf transpiration. The BPW34 has a relatively large sensing area of 7.5 mm^2, a light sensitivity from 430 to 1100 nm with a peak sensitivity at around 900 nm, and a wide angle of half sensitivity of 65° (Vishay Semiconductors, 2022). The photodiode is used in reverse bias mode with a 1K resistor according to the schematic in Figure 2.

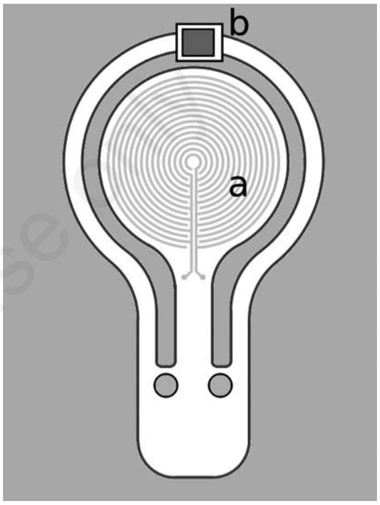

Figure 1. Schematic front view of the described leaf sensor. The central circular plate (a) with the interdigitated, concentric electrodes constitutes the capacitance sensor, and the photodiode (b) is visible on the top of the outer frame. The solder pads for wiring are placed on the back of the sensor.

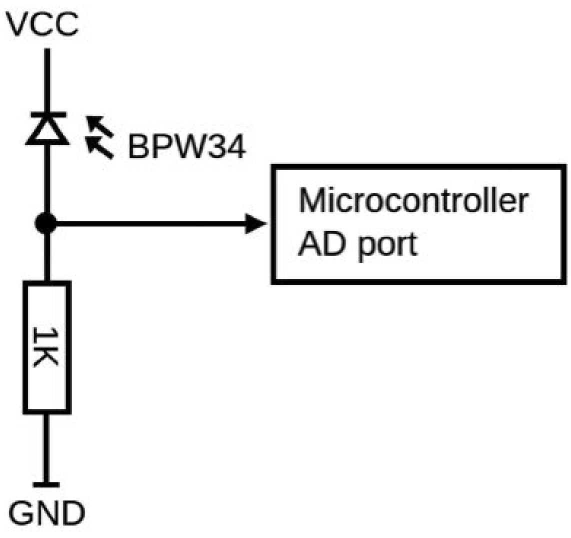

Figure 2. Schematic of the light-sensing circuit.

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The described sensor was tested in combination with a battery-powered, Arduino-based microcontroller, which retrieved the light and capacitance values at 10-minute intervals and transmitted the data to a web server via a connected LoRaWan module. Capacitance was measured according to the principle of a capacitive voltage divider, using the internal stray capacitance of the microcontroller board as reference capacitance (Nethercott, 2014). This enables capacitance measurements with the simplest possible circuit layout of only the two electrodes connected to the microcontroller board without needing additional components. Moreover, with the mentioned measurement interval, a relatively modest amount of less than 1 Kilobyte of data is generated per sensor and day.

Thermal camera imaging

The effect of the application of the sensor on the temperature of the adjacent leaf tissue was investigated with a thermal imaging camera (FLIR E95, FLIR Systems, Wilsonville, OR, USA). Repeated thermal images of grapevine leaves with attached sensors were taken during exposure to direct sunlight.

Tests under field conditions and on potted plants

The new leaf sensor was tested during the growing season of 2022 under field conditions for periods of up to six weeks on various perennial woody plant species (Figures 3A,B and 4), including apple (*Malus domestica* Borkh.), walnut (*Juglans regia* L.), persimmon (*Diospyros kaki* L.), olive (*Olea europaea* L.) and grapevine (*Vitis vinifera L.*).

Figure 3. A) Capacitive leaf sensor applied to the grapevine; B) Capacitive leaf sensor applied to the olive.

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Figure 4. View of the abaxial side of an apple leaf showing the lower side of a capacitance sensor.

The field test on grapevines was performed in a five-year-old, commercial Guyot-trained vineyard of the cultivar Pinot Blanc on SO4 rootstock growing in a deep sandy loam soil and with plant rows oriented in the north-south direction. Capacitive sensors were applied on fully expanded, sun-exposed, east-facing leaves and maintained in place for several weeks.

In addition, the new sensor was tested on three-year-old potted plants of the grapevine cultivar Pinot Blanc, grafted on SO4 rootstock, under conditions of progressive soil drying. The plants, already bearing grapes, were grown in plastic pots of 25 cm upper diameter and 25 cm depth filled with sandy loam soil. The surface of the pots was covered with a 3 cm deep layer of expanded clay pebbles for reducing soil evaporation and weed growth. The leaf sensors were fitted onto south-facing, sun-exposed leaves. Soil moisture sensors (CS655, Campbell Scientific Inc. Logan, UT, USA) were inserted into the soil for monitoring volumetric soil water content during cycles of progressive drying and renewed wetting. The pots were placed in open field conditions, and water was applied manually according to needs, bringing soil water content back to field capacity whenever the sensors revealed mild water stress.

Results

Thermal imaging

The thermal images of the leaves with applied sensors taken on several occasions revealed a distinct increase in the temperature of the sector of the leaf covering the sensor plate (Figure 5). The extent of this increase varied with climatic conditions and was directly related to the intensity and perpendicularity of solar irradiance. During intense sunlight, the temperature increase on grapevine leaves reached the most common values between 5 and 10°C.

Sensor performance

During the tests under field conditions and with potted plants, the described sensor proved robust and capable of providing reliably continuous readings. The open field tests on all examined plant species revealed a clear and consistent diurnal pattern of leaf transpiration, which, under unrestricted soil water availability, was closely related to the diurnal course of solar irradiance. Only during rainfall, the capacitance readings sometimes became inconsistent, probably due to water filtering into the narrow gap between the leaf blade and sensor plate, thus occasionally leading to erratic values.

The test on field-grown grapevines coincided with a period of limited rainfall and consequently with a gradual reduction of plant-available soil water. Figure 6 depicts the diurnal patterns of capacitance and irradiance readings on three selected days. As shown in Figure 7, the period preceding the first selected day was characterised by lack of precipitation and conditions favouring high plant transpiration rates. The second set of sensor readings was obtained after a spell of rain with 20 mm of precipitation, whereas the third set of sensor readings was recorded after two further days of high evaporative demand.

The diurnal capacitance patterns in Figure 6 indicate, for the first of the three depicted dates, a situation of incipient water stress, followed by a temporary recovery of plant water status after the rainy spell and a renewed situation of incipient water stress after two further days of warm and dry weather. The onset of mild water stress on the date (A) and (C) is evidenced by the typical decline of the diurnal course of sensor capacitance in comparison to the pattern of solar irradiance.

In the pot experiment, it was possible to relate sensor output directly to the progressive depletion of soil water. When volumetric soil water content approached about 10%, the sensor's capacitance started to decline and depart from its usual course closely correlated with irradiance. Capacitance readings remained after that low until re-watering when the course of capacitance readings quickly resumed its usual pattern imposed by light conditions. No evident symptoms of water stress were visible on the plants when stomatal conductance started to decline due to incipient water stress. Figure 8A and B shows an example of the capacitance sensor's output during six days of progressive soil water depletion followed by renewed water supply. On the day of the year (DOY) 158 (7 June), the registered capacitance values remained low due to overcast weather reducing irradiance and foliar transpiration. On DOY 159 and 160, capacitance readings were high due to intense solar irradiation and unrestricted soil water. On DOY 161, the declining availability of water caused an early drop of transpiration, which remained primarily inhibited also during the following day. After the pot was re-watered in the evening of DOY 162, the usual transpiration pattern resumed the next day.

Discussion

The thermal imaging results revealed a significant increase in the temperature of the sunlit leaf area covering the sensor plate. This temperature rise may be explained by the presence of the sensor plate, which modifies the leaf's energy balance by constituting a barrier to the dissipation of heat originating from the incident solar radiation. The lower temperature of the sensor plate, which follows along a falling temperature gradient, leads to the condensation on its surface of water vapour from stomatal transpiration and the ensuing changes in the dielectric properties. It may be assumed that the local rise of leaf temperature also determines an

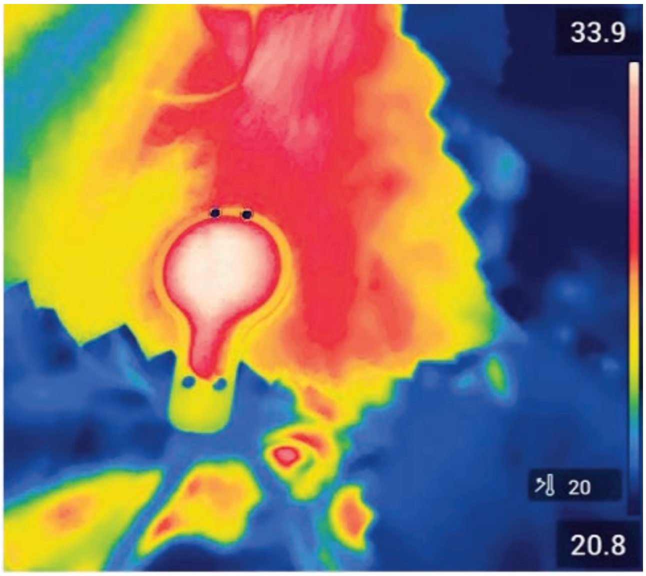

Figure 5. Thermal image of a grapevine leaf with an attached sensor.

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increase in transpiration due to temperature effects on the regulation of stomatal opening (Kostaki *et al*., 2020).

The amount of condensed water on the sensing plate at any given moment results from a dynamic equilibrium between vapour condensation and the simultaneous loss of water by evaporation through the narrow airspace between the leaf blade and sensing plate or by foliar reabsorption of water. The air space between the leaf blade and sensor plate is generally determined by veins protruding on the abaxial side of a leaf. Foliar reabsorption from the sensor plate may occur either by direct contact of the leaf epidermis with condensed water or indirectly through the vapour phase. It is known that plant surfaces, although mostly covered by a cuticle controlling loss and entry of water, show some degree of permeability to exogenous aqueous solutions, either through stomatal or cuticular penetration (Fernadéz *et al*., 2013). There is also evidence that many plant species can absorb rain, dew, or fog, thus affecting their water balance (Limm *et al*., 2009). It is, therefore, fair to assume that the reabsorption of water by the leaf contributes

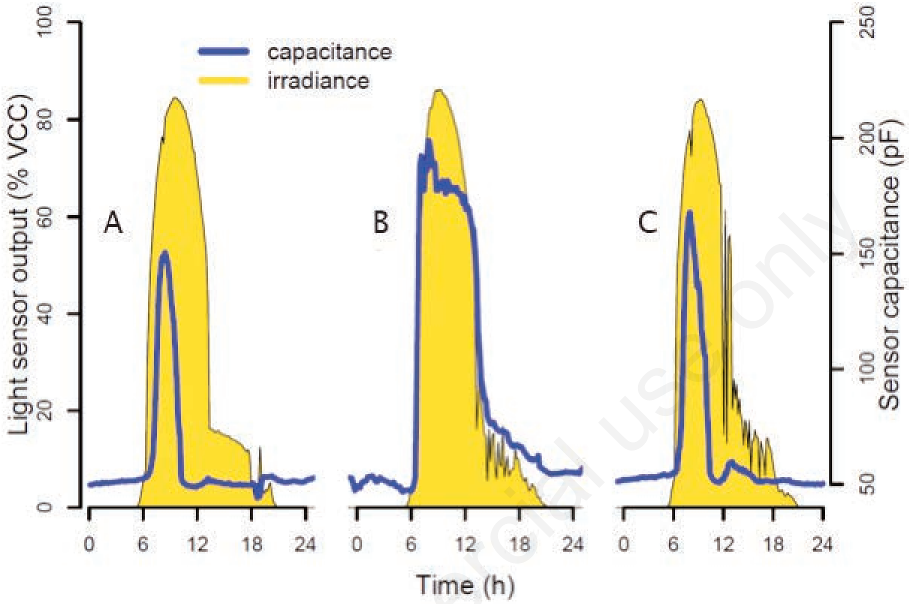

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Figure 6. Typical examples of diurnal patterns of irradiance and capacitance readings on a field-grown grapevine: incipient water stress after a dry period (A), fully recovered plant water status after a rainfall event (B), and the renewed onset of water stress (C). The meteorological conditions during this period are shown in Figure 7.

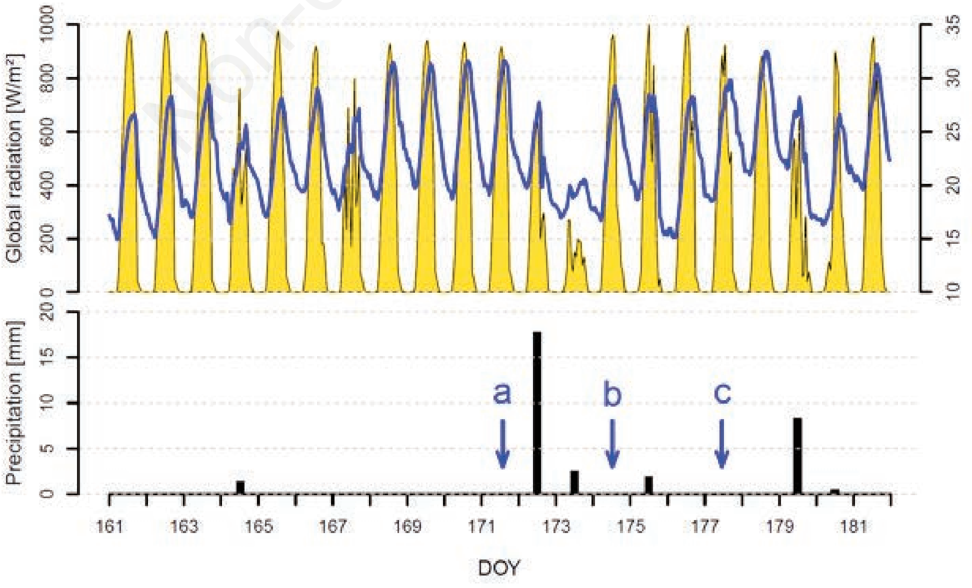

Figure 7. Global radiation, air temperature, and precipitation during the field test on grapevines. The arrows and letters indicate the days of measurement presented in Figure 6.

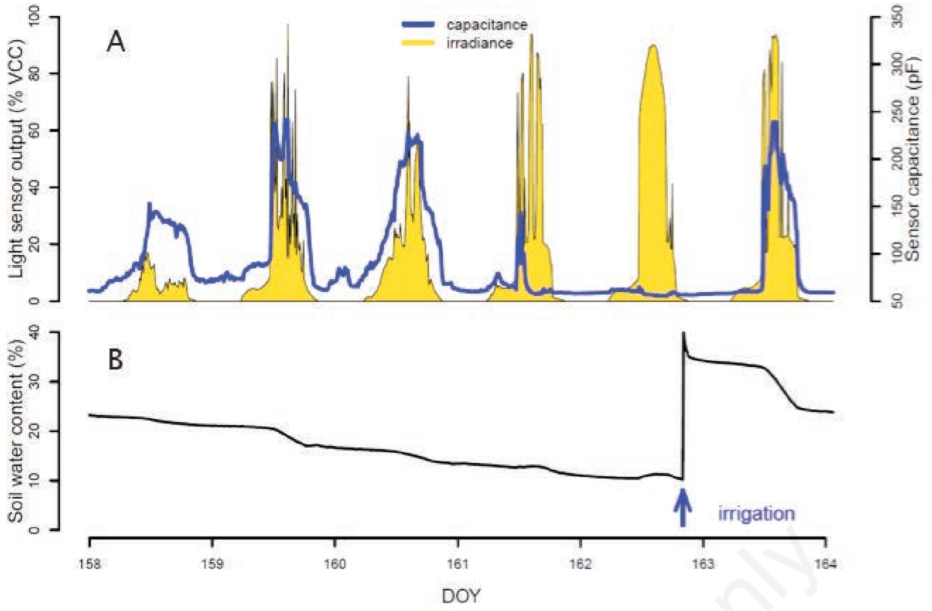

Figure 8. A) Diurnal patterns of irradiance and capacitance readings and B) soil water content during a six-day period of progressive soil water depletion and final re-watering of a potted grapevine plant.

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to the generally fast drop of sensor capacitance when solar irradiance declines.

The field observations and the pot experiment confirmed the ability of the sensor to monitor the time course of leaf transpiration under the influence of varying climatic conditions and available soil moisture. Sensor output on field-grown grapevine leaves clearly revealed incipient plant water stress after a dry period with high evaporative demand, and a temporary recovery of plant water status after a rainfall event. Similarly, the experiment with potted grapevines provided evidence of the sensor's efficiency through the close correlation between sensor output and soil water content.

Although the sensor cannot provide a quantitative measure of leaf transpiration, it can reliably reveal changes in the plant's stomatal behaviour caused by soil water depletion and high evaporative demand. The interpretation of the sensor output is based on the direct comparison of the time course of sensor capacitance with the pattern of solar irradiance. If the course of capacitance drops prematurely below the irradiance curve, limiting plant water availability might be the likely cause. The sensor detected the onset of drought conditions on grapevine plants well before the appearance of visible symptoms, which is a consequence of their efficient stomatal control of transpiration in response to mild water stress (Chaves *et al*., 2010).

The use of monitoring devices sensitive to foliar transpiration, such as the presented sensor, could lead to more efficient irrigation management by avoiding water supplies at times of unrestricted leaf transpiration or even by deliberately delaying irrigation until moderate plant water stress is achieved. Purposely exposing plants to moderate water stress could further improve their WUE since decreasing stomatal conductance affects transpiration more than photosynthesis (Steuer *et al*., 1988). Such strategies of intentionally exposing plants to periods of mild water stress are known as regulated deficit irrigation (RDI), which besides a more efficient use of water, often also provide advantages in terms of improved crop quality. In fact, strategies of RDI are receiving increasing attention for various permanent crops such as grapevine, almond, prune, cherries (Shackel, 2011), apple (Lo Bianco, 2019), citrus fruit (Mossad *et al*., 2018) and olives (Ben-Gal *et al*., 2021).

Previous research has investigated the use of capacitive sensors for the physiological monitoring of plant leaves. For example, Afzal *et al*. (2017) presented a leaf sensor with two small, coplanar capacitor plates revealing diurnal variations of capacitance, which they attributed to changes in the solute content of the leaves as an effect of photosynthesis. Currently, research is focusing on developing lightweight, plant-wearable sensors capable of monitoring physiological and environmental parameters. Sensors presented so far aim at measuring various parameters at the leaf surface, such as humidity (Lan *et al*., 2020), vapour pressure deficit (Yin *et al*., 2021) , or loss of leaf water content (Barbosa *et al*., 2022). This present sensor aims instead to detect vapour condensation as an indicator of foliar transpiration, simultaneously monitoring solar irradiance as its main driving force.

Further work may be required to investigate the influence of various factors on sensor performance, such as plant species, leaf type, leaf age, and meteorological conditions. Moreover, additional field tests will be needed to verify the sensor's long-term reliability and clarify how it can best be integrated into smart irrigation strategies of various crops and in a wide range of conditions, with a particular focus on crop performance and water economy.

Conclusions

The presented sensor allows the easy and inexpensive monitoring of leaf transpiration and solar irradiance in outdoor conditions and draws inferences about the plant water status by comparing the diurnal pattern of the two measured variables. The experiment with potted grapevines confirmed that the device could efficiently reveal plant water stress caused by progressive soil drying. The sensor also worked reliably on various other plant species in open field conditions over several weeks without adversely affecting the leaves. The simple and robust design, low cost, and the minimal power demand could make it a promising new tool for real-time plant monitoring and improved irrigation management.

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