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Review

Plant-Based Methodologies and Approaches for Estimating Plant Water Status of Mediterranean Tree Species: A Semi-Systematic Review

Gilbert Noun [1,*], Mauro Lo Cascio [1,2], Donatella Spano [1,2], Serena Marras [1,2] and Costantino Sirca [1,2]

1 Department of Agricultural Sciences, University of Sassari, Viale Italia 39a, 07100 Sassari, Italy
2 CMCC—Euro Mediterranean Centre on Climate Change Foundation, IAFES Division, Via De Nicola 9, 07100 Sassari, Italy
* Correspondence: gilbert.noun@gmail.com

Abstract: Global climate change presents a threat for the environment, and it is aggravated by the mismanagement of water use in the agricultural sector. Since plants are the intermediate component of the soil–plant–atmosphere continuum, and their physiology is directly affected by water availability, plant-based approaches proved to be sensitive and effective in estimating plant water status and can be used as a possible water-saving strategy in crop irrigation scheduling. This work consists of two parts: the first part extensively reviews the plant-based methods and approaches that are most applied to monitor the plant water status (PWS), the different technologies available, the gaps, and the possibility of further improvements in establishing a sustainable irrigation schedule. The various approaches are described, and the differences between conventional and recent improved methods are analyzed. The second part is an extensive dataset survey of 83 publications from 2012 to 2022 that applied the main monitoring methodologies and approaches for water status assessment in fruit and nut tree crops cultivated in a Mediterranean climate. The aim of this work is to serve as a practical reference to deepen reader knowledge on PWS and enhance researchers to identify gaps and potential advances in designing user-friendly monitoring technologies.

Keywords: climate change; irrigation scheduling; water stress; water saving; smart irrigation; precision Agriculture 4.0

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1. Introduction

Global climate change is a devastating threat for the environment due to the constant increase in average air and surface temperatures, as well as the erratic alterations of rainfall patterns [1]. The Mediterranean Climate Region (the Mediterranean basin, California, Central Chile, the Cape Region of South Africa, and the southernmost regions of Australia) in particular is affected by these drastic climatic oscillations that increase water deficits [2–4]. This directly alters agricultural productivity by causing a reduction in crop yields, particularly orchards and vineyards, damaging fruit's quality, and subsequently negatively impacting the economic sector [2,5–7]. In parallel, agriculture is the main consumer of water resources worldwide, and irrigated lands increase yearly to maintain the population's food demands [8]. Consequently, mismanagement of water use in the agricultural sector will aggravate the impact of climate change by increasing water losses [8,9].

Therefore, adaptation measures in irrigation measurement need to be implemented to guarantee efficient use of the available water, reduce water losses, and ensure both quality and quantity of crop yield [10]. Irrigation scheduling is, then, a priority, and improved and standardized methods are required to help farmers knowing when and how much water to apply while maintaining promising yields. Regulated deficit irrigation (RDI) strategies have been implemented as a way to balance drought periods and plant's irrigation needs during specific phenological periods [11–13]. RDI is a practice where crops are irrigated with an amount of water slightly below the crop coefficient during the least water stress-sensitive growing period with predefined water stress thresholds during each period [14,15], in order to improve crop production while saving water [16]. This approach was particularly successful in grapevines [17], olives [18], pomegranate [19], citrus trees [20], and peach [21], among others. On the other hand, it can negatively impact the yield in some crops, such as sweet cherry [22]. Therefore, for a remunerative and sustainable production process [23], an efficient plant-based irrigation program is needed, which strictly depends on the most sensitive indicator used to assess water stress per each crop.

In this regard, the plant water status (PWS) assessment is an approach that aims to help farmers elaborate an irrigation schedule as a possible water-saving strategy. Formerly, PWS was estimated based on soil water content, the readily available water, and the assessment of evapotranspiration [24,25], but such soil-based methods are highly influenced by soil texture [26,27], and soil water status indirectly affects plant growth rather than directly [28,29]. Additionally, plant physiological response to water deficit is affected essentially by changes in leaf and stem water content, rather than by soil water dynamics which are highly variable [27,30]. For these reasons, more recently, plant-based approaches proved to be more accurate and sensitive in estimating PWS [10,31,32], particularly in woody crops since the deep nature of their root systems presents difficulties in estimating soil water contents [33].

Plants are the intermediate components of the soil–plant–atmosphere continuum, and their physiology is directly affected by water availability [28,34]. Several studies analyzed and monitored PWS through various correlated physiological variables [33,35,36], whereas others focused on developing approaches, methods, and sensors that can operate continuously and remotely [37–39]. Stomatal conductance (g_s) [40], leaf turgor [41], stem diameter variation [42–44], leaf thickness (LT) [45], water potential [27,46,47], relative water content (RWC) [48,49], and sap flow (SF) [50–52] can be indirect indicators or proxies of water stress deficit. Each of these physiological variables has a certain response to water availability. In the case of water stress, the partial closure of stomata reduces water loss but simultaneously reduces photosynthetic activity and, thus, reduces growth and productivity [53]. Loss of turgidity affects cell enlargement by reducing plant growth and leaf area while increasing LT [54]. Moreover, trunk diameter decreases evidently, and shrinking is clear as water losses and evapotranspiration increase [55]. Lower water potentials may lead to complete desiccation or plant death [56]. On the other hand, the higher the RWC of a plant is, the greater it tolerates and survives under drought stress conditions. Sap flow decreases and shoot growth decreases when water is withheld [57].

Given the previously mentioned threats inflicted by climate change and the subsequent aggravated water scarcity in the semi-arid Mediterranean climate region in particular, there is an urgency to reform water management in the area through research and application. In fact, concern for limiting climate change impact and saving water in this jeopardized region, especially in the last decade [2,58–60], has led research to strive to satisfy the urgent need to ameliorate water management. Reviews describing plant-based methodologies have been previously published [10,32], but many new and improved techniques and approaches have been developed and assessed since. More importantly, these works offer a general technical overview of proxies, not accounting for their implementation under the distinct Mediterranean climate. Hence, the aim of the present work is to serve as an up-to-date reference for readers to understand PWS assessment. It will function as a guideline for engineers to design new technologies and sensors, technicians to plan modernized and improved irrigation systems, and agronomists to easily interpret and evaluate PWS. In parallel, it will enable researchers studying crop water stress under the drought conditions of the Mediterranean climate to build upon it for future advancement. To achieve this purpose, the work is divided into two parts. The first part reviews the approaches and methods developed to measure and estimate plant-based variables as proxy for assessing plant water status. For each water status variable, the different approaches, including current and more recent advancement in methods, are described and discussed.

The sensitivity and accuracy in estimating water status are outlined per each approach. The study also highlights the applicability of each approach for sustainable irrigation management, as well as the gaps and possible future technological improvements. In the second part of the work, the above-stated sensors and approaches implemented on Mediterranean fruit and nut tree crops are put into focus through an extensive dataset survey of studies from 2012 to 2022 to create a recent synopsis of dedicated research. The scope of this paper covers a total of 83 scientific works and describes the technology used, the main crops monitored, and the most active countries in this field, relatively.

2. Methods, Technologies, and Approaches to Monitoring Plant Water Status

The technical characteristics, strengths, and limitations of the methodologies and technologies are summarized in Table 1, while a graphic representation is portrayed in Figure 1.

Table 1. A summary of the main plant-based water stress indicators, measured variables, respective sensors and methods with their technical functions, and their main strengths and limitations for better irrigation scheduling.

Indicators, Measured Variables, Sensors, and Methods.	**Technical Function**	**Strengths**	**Limitations**	**Main References**
(1) Stomatal conductance g_s (maximum daily stomatal aperture) approach				
(a) Porometer	Computes g_s to Water Vapor (WV)	- Effective - Sensitive	- Handheld - Not automated - Leaf-to-leaf variation - Affected by nature of crop	[61]
(b) Infrared gas analyzer (IRGA)	Computes g_s to WV and CO_2			
(2) Leaf turgor (cell turgor pressure) approach				
(a) Cell pressure probe technique	Measures the turgor pressure equilibrium sap/oil	- Continuous and accurate measurement	- Invasive - Not suitable for long-term outdoor applications	[62,63]
(b) Leaf patch clamp pressure probe	Measures attenuated output pressure, in response to magnetic clamp pressure	- Noninvasive - Sensitive - Accurate - Continuous	- Possible leaf-to-leaf variation - Level of accuracy depends on crop	[64]
(3) Stem diameter variation (maximum daily shrinkage) approach				
(a) Dendrometer	Measures potential difference of either swelling or shrinking of the stem and translates it into an electrical signal	- Continuously and automatically recorded	- Affected by environmental changes and plant age - Variable and inaccurate	[65,66]
(b) Linear variable differential transformer	Converts linear displacements of the stem to an electrical signal	- Robust - High precision - Automated	- Needs individual calibration	[49]
(4) Leaf thickness approach				
(a) Micrometer	Pressure–volume curve.	- Automated	- Invasive method (requires leaf cut)	[67,68]
(b) Linear variable displacement transducers	Distance separating the sensor head of the metal target and leaf probe	- Noninvasive method	- Sensitivity limited by lateral shrinkage - Expensive instrumentation	[69]
(5) Leaf water content				
(a) Leaf Water Meter (LWM)	Measures leaf water content through the measurement of the absorption of radiation	- Noninvasive - Sensitive - Non-destructive	- Novel instrumentation	[70]
(6) Plant water potential (free energy of water) approach				
(a) Thermocouple psychrometer	Measure temperature and voltage variations due to vapor pressure	- Noninvasive	- Not automated	[71]
(b) Scholander pressure chamber	Balancing pressure measured with a pressure chamber and the osmotic potential of the xylem sap	- Simple - Effective	- Uses highly compressed gases - Time-consuming - Not continuous - Misrepresentation	[72]
(c) Pump-up pressure	Pressure applied by means of pump	- Avoids use of compressed gases - Mainly designed for irrigation scheduling and monitoring	- Novel instrumentation	[73]
(d) Microtensiometer	Sensor embedded in trunk to directly measure Stem Water Potential (SWP)	- Continuous - Accurate - Automated	- Underestimate SWP values below -1.5 MPa - Inaccurate measurement under high Vapor Pressure Deficit (VPD) condition	[74,75]
(7) Relative water content (relative amount of water present in the plant tissues) approach				
(a) Mass weighing	Weighing fresh, dry, and turgid masses of the leaf	- Easy to measure - Directly related to physiological function	- Difficult to obtain uniform replication	[48]

Table 1. *Cont.*

Indicators, Measured Variables, Sensors, and Methods.	Technical Function	Strengths	Limitations	Main References
(8) Sap flow (movement of fluid) approach				
(a) Heat balance method				
(i) Stem heat balance	Heat input from the heater to the entire circumference is balanced by the heat fluxes out of the stem	- Used for woody and herbaceous stems	- Invasive - Sensors are rigid and fixed - Cannot be used for thick stems	[51]
(ii) Trunk sector heat balance method	Heat applied to a segment of the stem	- Used for large stem diameters	- Invasive - Sensors are rigid and fixed	[76]
(b) Heat pulse method				
(i) Compensation heat pulse method	Heat pulse velocity is calculated by measuring temperature differences	- Consistent results	- Need to be corrected - Unable to measure low sap flow rates and reverse flow	[50]
(ii) Heat ratio method	Measures the ratio of the increase in temperature	- Measures reverse flow	- More accurate than Compensation Heat Pulse Method (CHPM) - Less reliable at high flux densities	[77]
(iii) T-max method	Calculates time delay for a maximum temperature rise to occur at the downstream temperature sensor	- Single temperature sensor - Measures simultaneously the heat wave at several depths in the trunk	- Noisy measurements at night - Unable to measure low flow rates	[78]
(iv) TmRatio heat pulse method	Calculates heat pulse velocity using the ratio of the maximum temperature increase between the downstream and side probe	- Low-cost - Easily replicated - Able to measure low flow and at night	- Novel instrumentation	[79]
(v) Sapflow+ method	Calculates conduction and convection of a short-duration heat pulse	- Nondestructive measurement of high, low, and reverse sap flows	- Requires temperature correction	[80]
(vi) Single probe heat pulse	Measures sap velocity using a probe	- Simple and small size, less physical damage, less errors	- Unreliable in determining low sap velocity	[81]
(vii) Dual heat pulse method	Measures diverse flow ranges such as low and high flow rates, as well as reverse flows, using two heat pulse techniques	- Effective in tracking water demands associated with changing microclimatic conditions	- Limited efficacy (research purposes)	[82]
(c) Continuous heat method				
(i) Thermal dissipation probe	Calculate temperature difference between two probes	- Simple - Accurate - Low-cost	- Needs calibration - Errors in estimating sap flow for whole tree - High electrical consumption	[83]
(ii) Heat field deformation method	Continuous linear heating system	- Shows plants' responses to sudden environmental changes and water stress - Measures at different depths in the sapwood, high, low, and reverse flows	- Can cause errors in estimations	[84]

2.1. Stomatal Conductance-Based Approach

In the leaf, the role of stomata is to regulate carbon dioxide (CO_2) assimilation with respect to water vapor (WV) loss. Although water loss through transpiration during high-temperature conditions cools down plants, stomatal closure during drought periods is crucial to limit transpiration and prevent possible xylem dysfunction [61,85]. Therefore, stomatal regulation of leaf gas exchange is vital for plant survival under arid and semi-arid conditions when potential evapotranspiration is above precipitation [10,86].

The measurement of stomatal aperture or g_s is the inverse of the stomata resistance to the rate of passage of CO_2 entering and WV exiting the leaf. Many variables, such as alternations in soil water status and atmospheric demand, cause the stomatal aperture to change regularly [87,88]. The constant variation of g_s measurements reflects the plant response to water stress and is considered one of the most effective and sensitive water stress indicators [32,89]. The maximum daily g_s (g_{smax}) is the g_s value measured at the broadest possible stomatal aperture when optimal gas exchange is achieved and is widely considered a water stress indicator [10].

The g_s is measured using porometers and infrared gas analyzers (IRGAs). The porometer computes g_s to WV, whereas the IRGAs compute g_s to both WV and CO_2. Both devices have a chamber in which the whole leaf, or part of it, is clamped. If the leaf cuticle is permeable to WV and CO_2, the apparatus measures the leaf conductance (g_l). If the leaf has an impermeable cuticle, the device computes the g_s. Toro [90] showed that the measured g_s strongly differed between the IRGA and the porometer depending on the plant species, water availability, and environmental conditions. Under maximum water stress, g_s measured with the leaf porometer was higher than those measured with the IRGA.

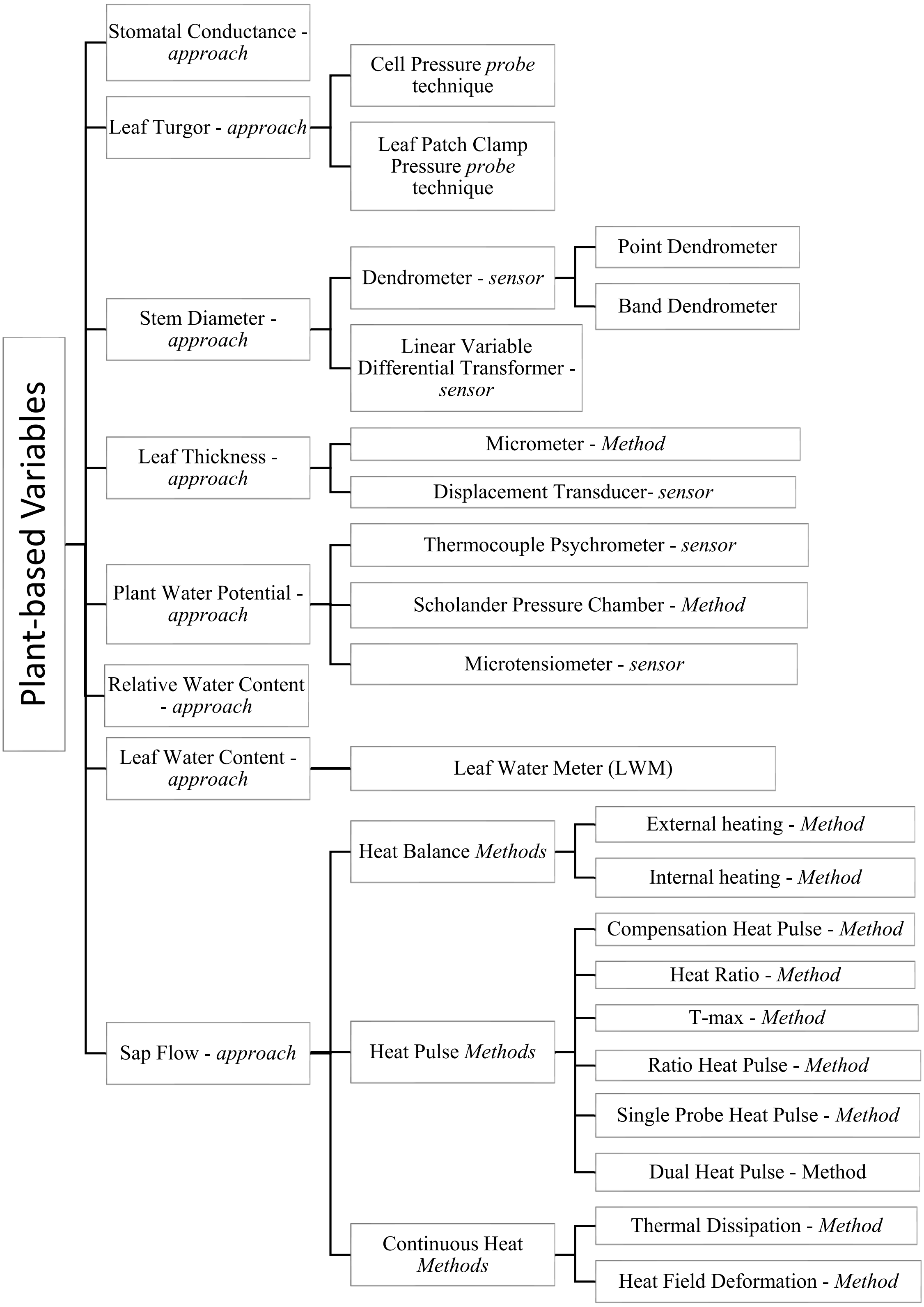

Figure 1. Graphical scheme describing the different plant-based variables and approaches, and the respective technology or sensors used to estimate plant water status. The approaches measure physiological variables by means of different methods and instruments.

2.2. Leaf Turgor-Based Approach

Leaf turgor is the pressure exerted on the cell walls to maintain its rigidity and form. The leaf loses rigidity and wilts because of water stress and deficit. The osmotic flow of water regulates this pressure. Stomatal closure and aperture control transpiration, which in turn affects leaf water status and subsequently leaf turgor pressure [91]. The decrease in turgor pressure was shown to be directly proportional to the transpiration rate and stomatal closure [41,92]. After studying diurnal oscillations of turgor pressure, Zimmermann [93] also found that leaf water status can be evaluated according to the size of turgor pressure loss around noon and the time needed for its recovery in the afternoon.

2.2.1. Cell Pressure Probe Technique

The cell pressure probe technique was introduced as a method intended to continuously measure cell turgor [62,63,94,95]. The pressure probe comprises a microcapillary, a pressure chamber containing a pressure transducer, and a metal rod, with the whole device filled with silicone oil. The probe is then attached to the leaf by inserting the microcapillary into the cell, and pressure is exerted by releasing the oil. Consequently, turgor pressure pushes the sap to exit the cell into the microcapillary, decreasing the cell pressure. Again, oil is released, causing an increase of pressure until the boundary sap–oil reaches an equilibrium, and the pressure on the oil read by the pressure transducer becomes equal to cell sap. This technique is accurate, robust, and straightforward in determining leaf turgor [96].

2.2.2. Leaf Patch Clamp Pressure Probe

More recently, researchers studied a noninvasive leaf patch clamp pressure probe (LPCPP) designed to measure leaf turgor [64,97,98]. The probes are made up of pressure sensors clamped to the leaves using two magnets to monitor relative water status changes. To consider the measurements accurate, the patches should be in osmotic contact with the whole leaf, and the stomata should be closed to avoid water loss. For these conditions to be achieved, the upper magnet can be moved and clamped according to LT and rigidity, while keeping constant the pressure exerted by the magnets. The probe measures the pressure transfer function of the leaf patch, i.e., the attenuated output pressure (Pp), in response to the magnetic clamp pressure (Pclamp), with cell turgor pressure (P_c) measured on the leaf patch being opposed to this output pressure (P_p) [64,99].

A non-invasive magnetic LPCPP (the ZIM-Probe) was developed by Zimmermann [100] to measure changes in leaf turgor continuously and in real-time.

2.3. Leaf Thickness

The first studies dedicated to the relationship between LT and PWS showed a decrease in LT during plant dehydration, followed by a rapid compensation upon irrigation, causing changes in leaf and stem thickness indicators of water deficit [45]. Studies showed a correlation between LT and plant water potential [67,69], providing an early stress detection measurement. More recent studies showed that LT can be used to measure leaf RWC and overall plant water content [101].

LT can be measured using micrometers [67,68] or using the linear variable displacement transducers, also known as linear variable differential transformers (LVDTs), that similarly measure stem diameter [69].

2.3.1. Micrometers

The sample leaf is cut and submerged in water after being inserted in a polyethylene bag to prevent evaporative water loss, and then stored in darkness. The leaf is allowed to regain full hydration before measuring its thickness at full turgor. The gear-wheel type micrometer is used to measure LT through an internal spring that exerts pressure when released. A pressure–volume curve is then constructed to calculate thickness and RWC [67,68]. Micrometers are considered bulky and hard to automate [101].

2.3.2. Displacement Transducers

A displacement transducer is a device consisting of a leaf clamp holding a probe and a metal target or rod [69]. When the instrument is clamped around a sample leaf, an alternating current passes through the probe, generating an alternating magnetic field that induces eddy currents within the target. The circuit is then transformed into a voltage and linearized as a function of the distance separating the sensor head of the metal target and the leaf probe, this distance being the LT. These transducers were introduced in an attempt to allow automated LT measurement [102].

2.4. Leaf Water Content

The authors of ref. [70] introduced a novel sensor, the leaf water meter (LWM), that measures leaf water content through the measurement of the absorption of radiation when this propagates through the leaf tissues. The non-invasive tool is based on the photon attenuation of the passage of radiation through the leaf. Three plastic clamp cables are connected to a readout system, which is equipped with climatic sensors. LWM was shown to be a sensitive, non-destructive, and reliable device to monitor plant water status continuously and in real-time during water stress progression.

2.5. Stem Diameter-Based Approach

Stem diameter variation (SDV) is a PWS indicator that permits the early detection of water stress. A strong relation exists between daily variations in PWS and daily variations in stem diameter [42–44,103–105]. As transpiration (Ep) occurs in the plant leaves, a tension arises in the evaporative surface and extends to all water-storing organs. This rapid response to atmospheric changes causes systematically diurnal diameter changes in all plant parts, including the stem, branches, roots, leaves, and fruits [105–109]. As a result, as Ep increases, water loss increases, leading to a decrease in trunk diameter.

Nevertheless, these changes in water content represented by shrinkage and swelling of the tissues are reversible, leading to diurnal SDV. Daily, the fluctuations record SDV-derived variables: a maximum daily stem diameter and a minimum daily stem diameter, with the difference between them being the maximum daily shrinkage (MDS). Another recorded measurement is stem growth rate, which corresponds to the difference between the maximum stem diameter of two consecutive days [110,111]. Significant differences in stem diameter variation under different irrigation levels exist as water shortage results in larger maximum daily shrinkage and smaller daily increase [112].

2.5.1. Dendrometers

Dendrometers are instruments used to measure stem and trunk diameter variation and growth. They give high-resolution data of diurnal stem size variations and seasonal tree growth and water storage fluctuations over the year [65,104,113].

Point Dendrometers

Point dendrometers measure stem growth along the radius or diameter of a tree using a linear potentiometer or sensor consisting of a rod nailed or screwed outside the trunk. The sensor measures a potential difference of either swelling or shrinking of the stem, and translates it into an electrical signal [66]. An output voltage will then be obtained, indicating the stem's growth.

Band Dendrometers

Band dendrometers measure the circumference and linear displacement of a band wrapped around the trunk, stem, or branch using a linear potentiometer. Similar to the point dendrometer, as the stem swells or shrinks, the band expands and contracts, transmitting a signal to the potentiometer [65].

2.5.2. Linear Variable Differential Transformers

LVDTs are sensors fixed on the main trunk by a metal frame of Invar, a metal alloy with minimal thermal expansion. They function by converting stem linear displacements they are coupled to into an electrical signal through a displacement transducer. The sensors should be individually calibrated using a precision micrometer. The LVDT sensors are robust and of high precision [110]. They are sensitive to small changes in stem growth.

2.6. Plant Water Potential-Based Approach

Water potential or free water energy measures the potential energy of water that allows water to move up the plant [114].

Leaf water potential (LWP) is measured on a single leaf and can represent local leaf water demand, soil water availability, internal plant hydraulic conductivity, and stomatal regulation [46,115]. Xylem water potential (XWP) is measured on a non-transpiring leaf since, when leaves do not transpire, their potential is considered to correspond to stem water potential (SWP) [7,116]. XWP is the result of whole-plant transpiration and soil and root/soil hydraulic conductivity. Subsequently, it indicates the ability of plants to conduct water from the soil to the atmosphere [116]. Studies showed SWP to be a water deficit indicator [35,117,118], and since SWP is equal to XWP, it can replace LWP as a more accurate water stress indicator [27,119]. According to Van Leeuwen [7], under conditions established by dry soil cultivation, plants tend to maintain LWP, especially at midday, through increased stomatal closure to avoid severe water losses. Furthermore, Choné [46] established a relationship between leaf transpiration and $\Delta\Psi$ for grapevines. PWP is measured using three main methodologies: thermocouple psychrometers, pressure chambers and Scholander pressure chambers [68,72,120,121],and more recently, the microtensiometer [74,75,122].

2.6.1. Thermocouple Psychrometers

Thermocouple psychrometers are noninvasive instruments that measure leaf water status on site. Isopiestic psychrometers work by enclosing the sample leaf and a thermocouple in a small container or chamber while maintaining constant temperature [71]. The thermocouple is made up of two junctions: the reference junction, which measures the chamber temperature, and the measurement junction, which measures the air temperature. As water evaporates from the leaf, air humidity is measured, and water vapor pressure is determined. When evaporation takes place, vapor pressure increases, and subsequently, temperature and voltage detected by the thermocouples decrease. Contrarily, when condensation occurs, vapor pressure drops, and temperature and voltage increase. Nevertheless, when the temperature is kept stable, and neither condensation nor evaporation occurs, vapor pressure is considered equal to air humidity, thus equivalent to the plant water potential [71].

The water activity meter is considered a subgroup of the psychrometer technique that measures plant water potential based on the chilled-mirror dewpoint technique [123,124]. The instrument is made up of a sealed chamber that contains a mirror and a means of detecting condensation. At equilibrium, the water potential of the air in the chamber is equivalent to the water potential of the sample.

2.6.2. The Scholander Pressure Chamber

The Scholander pressure chamber is a simple and effective instrument widely used to measure LWP [72]. The method consists of increasing the pressure using a high-pressure compressed gas around a leaf until sap from the xylem appears at the end of the shoot, extends outside the chamber, and is exposed to atmospheric pressure [71]. The pressure needed to keep this condition is equal to the negative pressure existing in the intact stem. The quantity of pressure necessary to force water out of the leaf cells into the xylem is a function of the water potential of the leaf cells [71]. LWPs are then estimated from the sum of the balancing pressure measured with a pressure chamber, and the osmotic potential of the xylem sap in leafy shoots or leaves.

The pump-up pressure chamber is a newly designed pressure chamber that avoids the use of compressed gases in the Scholander design, achieving the required pressure through a pump [73]. This novel pressure chamber is mainly designed for irrigation scheduling and monitoring, particularly for managing deficit irrigation.

The authors of ref. [125] proposed modifications in the sampling technique to obtain more accurate and consistent results, emphasizing the knowledge and proper training of the operator.

2.6.3. Microtensiometer

Since the previous methods do not measure water potential continuously and are labor consuming, microtensiometers were studied as an option for continuous monitoring of water status [74,122]. These sensors measure water potential based on a microelectromechanical pressure sensor that is embedded in the trunk and directly measures stem water potential. This method can be automated, providing continuous data in easy-to-interpret pressure units similar to the traditional pressure chamber stem water potential methods [122]. Blanco and Kalcsits [74] found that microtensiometers gave accurate continuous measurements of SWP in trees during the growing season across a large range of environmental conditions and soil water content. On the other hand, the author of ref. [75] found that microtensiometers are sensitive in representing diurnal and seasonal changes in water potential, except under high VPD conditions.

2.7. Relative Water Content-Based Method

RWC represents the relative amount of water present in the plant tissues, i.e., the correlation of the actual water content of a tissue to the highest attainable water content at full turgor [126]. It is used as a water deficit indicator [37,127,128]. Diurnal RWC is closely related to stem diameter changes and varies inversely with the change in solar radiation, increasing when the radiation decreases and decreasing as radiation increases [49]. Mathematically, the RWC of plant tissue is calculated according to Equation (1)**.** [48]:

$$\text{RWC}\ (\%) = [(\text{FW} - \text{DW})/(\text{TW} - \text{DW})] \times 100 \quad (1)$$

FW, DW, and TW are the fresh, dry, and turgid masses, respectively, of the tissue.

FW is the mass weighed immediately after leaf collection, TW is obtained after floating the leaf in distilled water, and DW is the weight taken after placing the leaf in a heated oven.

2.8. Sap Flow-Based Approach

SF is the movement of fluid in the roots, stems, and branches of plants, and is typically measured in the xylem of plants [129]. The measurement of the rate at which the sap ascends a plant, whether the whole plant, individual branches, or tillers, can determine the transpiration rate. Since transpiration depends on PWS, and given that the effect is controlled by stomatal opening and g_s, SF can be used as an indicator of PWS and water stress [129–131]. According to Alarcón [130], SF is greatest on warm, sunny days of high vapor pressure deficit, and the least on cooler, cloudy days of low VPD. Additionally, SF would decrease progressively once irrigation water is suspended, and vice versa, increase when irrigation is resumed [130].

Two main approaches exist to measure SF: one calculating the sap-flow rate through the heat balance methods, the other calculating sap-flux density through either the heat pulse methods or the continuous thermal dissipation methods [131].

SAPFLUXNET is a global database of SF measurements [132]. The metadata surveys SF datasets from field studies on species around the globe in order to serve as a benchmark for research.

2.8.1. Heat Balance Methods

Heat balance methods calculate the mass of flow rate of sap, determining, by difference, the amount of heat transported in the moving sap after being subjected to a known amount of heat.

Heat Balance with External Heating, or Stem Heat Balance Method

The stem heat balance (SHB) method, introduced by Sakuratani [51], is used to measure SF in both woody [133] and herbaceous [134] stems. A SHB gauge is made up of a flexible heater (thermopile) and thermocouples to sense temperature differences wrapped around the conductive organ. A small quantity of heat is then applied continuously through the heater, and the connected thermocouple junctions sense the increase of temperature of the enclosed stem.

Energy conservation between the energy put into the stem and the energy losses is calculated, i.e., the heat input from the heater is balanced by the heat fluxes out of the stem, thus obtaining SF [51,134].

Heat Balance with Internal Heating, or the Trunk Sector Heat Balance Method

The trunk sector heat balance method of SF measurement used on tree trunks with diameters greater than 120 mm. Similarly to the stem heat balance method, SF rates are derived from the heat balance of a heated stem tissue. However, in the trunk sector heat balance method, heat is applied internally to only a segment of the trunk, instead of externally to the entire circumference of the enclosed stem. Stainless steel electrode plates, as well as thermocouples, are inserted into the trunk to transfer heat. Temperature increase ΔT between the inside and the outside of the trunk is calculated to measure the SF rate at the center of the heated trunk sector [76].

2.8.2. Heat-Pulse Methods

Heat-pulse techniques are noninvasive methods used to measure SF in plant stems without disrupting the sap stream of the conductive organ [52,78,135]. The obtained measurements are consistent, use low-priced technology, and provide a good time resolution of SF, as well as automated data collection and storage [136]. The sequential or simultaneous measurements on numerous trees can estimate transpiration from whole stands of trees [135].

Compensation Heat Pulse method

The compensation heat pulse method (CHPM), introduced by Marshall [50], is a technique intended to study SF [130,137–139]. Since its introduction, simple instrumentation, robust probes, and reliable measurements have been developed [136].

This technique uses two temperature probes asymmetrically placed on either side of a central line heater inserted radially into the tree xylem through drilling holes into the sapwood. The heater probe then releases a heat pulse that is then carried via convection and conduction as a tracer in the conducting organ. The heat pulse velocity is then calculated by measuring temperature differences, with the application of a set of theoretically derived corrections to correct errors that might occur due to a stem wound following the drilling [52,135,138].

The comparison between the values of SF and transpiration rates measured underlined the robustness and high sensitivity of the compensation heat-pulse technique for estimating transpiration [136,140].

The Heat Ratio Method

The heat ratio method (HRM), an improved heat-pulse-based technique, was developed by Burgess [77] to modify the CHPM.

The HRM measures the ratio of the increase in temperature, following the release of a heat pulse through a central heater, at points equidistant downstream and upstream. With the HRM, placement errors of the equidistant probes can be tested in situ and mathematically corrected, making it more accurate than CHPM asymmetrical probes [77].

The velocity of the heat pulse can be calculated from the temperature ratio between the two sensor probes, the thermal diffusivity of the sapwood, and the distance between the heater and the sensor probes [50,77], and then converted into sap flux density [77,141].

A recently developed external heat ratio (EHR) method aims to obtain a noninvasive and accurate bidirectional SF, and is further adapted to thin stems [142,143]. The EHR consists of a small heater and two thermocouples installed on the stem equidistantly, a few millimeters from the center of the heater.

T-Max Method, The Cohen's Heat-Pulse Method

Marshall's [50] analytical theory was used by Cohen [78] to develop an alternative improved heat pulse method, the T-max method, which, as opposed to other heat-pulse methods that rely on two temperature sensors or thermocouples, uses a single temperature sensor inserted downstream of the line heater. This method simultaneously measures the heatwave at several depths in the trunk by recording the time delay for a maximum temperature rise at the sensor location. A second probe located upstream of the heater serves as a reference probe to compensate for any background changes in stem temperature during the T-max measurement. SF is then determined from the time delay for a maximum temperature rise to occur at the downstream temperature sensor.

Green [138] described the procedure used to convert raw heat-pulse data into values of volumetric SF by presenting a set of theoretical correction factors for this purpose.

The Ratio Heat Pulse Method

Miner [79] developed the T_mRatio method using a gauge consisting of three needle probes: the central probe applies a heat pulse, one temperature probe located above the heater probe and the other placed on the side of the heater. The aim is to calculate heat pulse velocity using the ratio of the maximum temperature increase between the downstream and side probe.

The Sapflow+ Method

Vandegehuchte and Steppe [80] developed a sap flow method that simultaneously measures sap flow density and stem water content, without disrupting the sap flow. The combination of determining heat velocity and water content results in the sap flux density values. These parameters are determined based on the conduction and convection of a short-duration heat pulse, a finite length away from an infinite line source in the anisotropic sapwood. The sensor is formed of a four-needle probe consisting of a linear heater and three measurement needles located at specific distances axially upstream, downstream, and tangentially from the heater [80].

Measurements can be conducted at different depths to obtain a radial sap flux density profile. Therefore, heat velocity, axial, and tangential thermal conductivity, as well as volumetric heat capacity, are thus derived after fitting the correct heat conduction–convection equation to the measured temperature profiles.

Single Probe Heat Pulse Method

The authors of ref. [81] presented and tested a new heat pulse method using a single probe, called the single probe heat pulse (SPHP) to monitor sap velocity. This method uses a single needle as opposed to the two to four needles needed in the other traditional methods. The advantages of a single-probe sensor, apart from its simplicity and smaller size, is the decreased physical damage from the insertion of the needle, the lesser thermal trauma and power requirements, in addition to the prevention of measurement errors. Nevertheless, this method was shown to be unreliable in determining low sap velocity [81]. The authors of ref. [144] developed an improved single probe method with finite heating duration (F-SPHP) to enlarge the SF density measurement range even at low flow rates. Compared with

Sapflow+, F-SPHP needed calibration to enable water content determination. These single probe methods, combined with their simplicity and low cost, present many advantages compared to multi-probe methods [81,144].

Dual Heat Pulse Method

The authors of ref. [82] validated the combination of two heat pulse techniques, HRM and CHPM, in a single set of sensor probes, the dual SF sensor. The integration of the methods allows the measurement of diverse flow ranges such as low and high flow rates, as well as reverse flows. This novel sensor proved to be effective in tracking water demands associated with changing microclimatic conditions. Nevertheless, its efficacy was limited to research purposes due to the variability of the sensors, needing to be evaluated against other techniques [82,136].

2.8.3. Continuous Heat

Thermal Dissipation Probe

Granier [83] developed a simple yet accurate and low-cost constant heating method to relate the dissipation of heat to sap flux density empirically. The thermal dissipation SF meter is composed of two probes inserted radially into the xylem. One of the two probes, the thermal dissipation probe, is heated with constant energy input. In contrast, the other, the reference probe, remains unheated, i.e., keeps the same ambient temperature of the wood. Sap flux density is then calculated as a function of the temperature difference between the two probes, assuming that under thermal equilibrium conditions of the system and constant sap flux density, input of heat is equal to heat dissipated by convection and conduction [83,145]. This technique requires species-specific calibration to allow accurate SF measurements [141,146]. Alizadeh [147] developed a new sensor that aims to overcome the limitations of the thermal dissipation probe. The novel trunk RWC sensor (TRWC) includes, in addition to the two probes, a microprocessor and data acquisition, data processing, and heater control system. The microprocessor turns the heater on and off according to temperature changes in the trunk, and then correlates the elapsed time with the water content. The TRWC is designed to reduce the effect of outside temperature.

The Heat Field Deformation Method

The heat field deformation (HFD) method [148] enables sap flux density measurements to be made through a continuous linear heating system. This constant heating technique shows plant responses to sudden environmental changes and water stress. The sensor used comprises a needle-like heater radially inserted in the sapwood and two pairs of differential thermocouples. The lower reference thermometer of the asymmetrical pair of thermocouples is then positioned in one common needle and placed below the heater. The upper thermometer is placed next to the heater, whereas the thermometers are positioned equidistantly from the heater in the symmetrical pair of thermocouples. This placement allows simultaneous recording of the dissipation and deformation of heat in axial and tangential directions around the linear heater [148]. The HFD method measures both asymmetrical and symmetrical temperature gradients, dT_{sym} and dT_{as}, respectively. It, therefore, eliminates any limitations in the measurements due to the separate application of thermometers as in other methods.

The $dT_{\text{sym}}/dT_{\text{as}}$ ratio thus calculated is proportional to SF rates [148,149], and dT_{sym} is also known as the SF index, which can be used as a stress indicator [148]. The method is designed to measure SF measurements in tree organs with a diameter greater than 3 cm, as well as those with a diameter less than 2 cm using baby sensors [150,151].

3. The Application of Plant-Based Indicators in Irrigation Scheduling

The PWS should be monitored very carefully to sustain and optimize irrigation management, prevent water waste, and avoid excess stress for plants that can adversely affect crop yield. The physiological variables studied for the main crops grown in the Mediterranean climate region, describing the strengths and limitations of each method or approach, are listed in Table 1.

3.1. Stomatal Conductance

Stomatal closure is one of the most effective and sensitive plant responses to water stress, and its monitoring is widely used in irrigation scheduling. Nevertheless, g_s has its limitations. First, the sizeable leaf-to-leaf variation requires considerable replication to obtain reliable data [32]. Second, the devices used to measure g_s are handheld and managed manually, and therefore are labor-intensive and not readily automated. In an attempt to automate the measurement of g_s, the authors of ref. [152] reported a method to estimate g_s from values of radial sap flux density and vapor pressure deficit of the air. These two variables can be continuously and automatically recorded under field conditions.

When g_s is considered a stress indicator, specific leaves at specific positions and timings should be monitored, since stomata frequently change their conductance depending on environmental conditions [153]. Additionally, the isohydric and anisohydric nature of the plants affects the leaf water status through controlled stomatal closure. Similar to maize and cowpea, isohydric species regulate leaf water status over a wide range of atmospheric demand and soil water content [154]. On the other hand, anisohydric species such as sunflower or barley are less effective at controlling leaf water status through stomatal closure [154].

In contrast, some species such as grapevine may show isohydric or anisohydric behavior, depending on the water stress conditions [155,156]. This isohydric and anisohydric behavior can limit the accuracy of the reliance on g_s alone. Another limitation is that the sensors used to measure g_s are not automated. The sensitivity of g_s to PWS changes was shown to be a good irrigation indicator for several crops [32,157,158]. It was studied in the application of an irrigation schedule in olives [159], grapefruit [160], and grapevines [161], among many others.

3.2. Leaf Turgor

Leaf turgor measurements can be run continuously and automatically, specifically using the LPCPP or ZIM-probes, accurately representing PWS and sensitive changes [38,39,162–165]. These new non-invasive probes can monitor the effects of air and leaf temperature, air relative humidity, illumination, and wind on turgor pressure [100]. Additionally, the developed probes are designed to send the data about the water status wirelessly through the cloud, enabling the timing of irrigation and the precise amount of water to be adjusted as needed. This method can be controlled remotely by telemetry, where the obtained data is transferred directly to a dedicated server. Short-term and long-term temporal and spatial dynamics of leaf water status can thus be detected with high precision and real-time [98]. The patch-clamp pressure probe can give sensitive, accurate, and distinguished turgor pressure measurements given microclimatic changes, as well as alterations in irrigation [93]. Nevertheless, many sensors need to be mounted to provide a global idea of the field water status, which can be expensive for farmers [166]. Furthermore, clamping the sensors for a long duration can cause damage to the leaf surface, suggesting that it is most practical for thick leaves such as olives [166].

A fully automated irrigation system based on leaf turgor was found to be sensitive and accurate in detecting water needs in citrus and avocado [167]. In olives, an irrigation scheduling approach based on the automated measurement of leaf turgor was shown to be effective and easy to apply by farmers for both young and fully mature trees [163]. In grapevines, leaf turgor showed sensitive responses to changes in PWS. It can be used as an indicator for establishing an irrigation regime in grapevines, even under an unsettling environment [98,99]. Nevertheless, the actual leaf turgor measurements can be dependent on the level of water stress, and need further studies on the data to be considered reliable in irrigation scheduling [162,168].

3.3. Stem Diameter

The SDV outputs are accurate and sensitive water stress indicators and can be easily automated at a field scale, giving them great potential for irrigation scheduling [110,169]. Nevertheless, they are highly affected by seasonal growth patterns, plant age and size, and crop load [110,170], and they might show plant-to-plant variability [110], calling for many measurements to be made [170]. Therefore, the complex results impose the necessity of expert interpretation before being applied in any irrigation schedule, limiting their potential for an automated calculation [171]. The limitation of point dendrometers is that they measure only one side of the stem, and therefore, many experimental repetitions should be held in order to achieve accurate results, whereas band dendrometers underestimate tree growth, and they may not be able to measure the hourly diameter change of small diameter branches [172]. Although point dendrometers are considered more accurate and more precise in dealing with wood formation than band dendrometers [104,173], they have the limitation of needing maintenance due to interference from insects and spiders [104]. Moreover, the applicability of an SDV-derived index should be tested for field conditions [33].

Despite these limitations, they are often used in irrigation schedules since they are continuously and automatically recorded. In studies done on olive, variations in stem diameter were shown to be the most sensitive indicator for accurate automated irrigation scheduling in young olive trees, in contrast to mature trees [174].

Calculated MDS is considered a key indicator of the PWS [21,55,175,176]. Its measurement can be easily and continuously automated, which would be considered a limitation for the measurement of LWP or SWP [35,110].

In peach, the continuous MDS measurements are sensitive enough to detect early changes in water status, and thus prevent water stress and damage, and can be used alone as an indicator for water status and irrigation scheduling [174,177,178]. Similarly, in grapevine, cherry, and apples, MDS proved to be a sensitive indicator for the early detection of water stress [35,36,179]. Apart from its sensitivity, the continuous and automated monitoring of changes in stem diameter makes it a better tool than LWP, which needs to be manually measured once per day. In contrast, Martín-Palomo [111] concluded that MDS was not a useful indicator for irrigation scheduling in almonds because of the great trunk growth, suggesting the tree growth rate as a more sensitive stress indicator. In citrus [180] and avocado [105], it was found that absolute MDS values show large day-to-day variations due to the variable environmental conditions. Elsayed-Farag and Melgar [180] suggested the use of the MDS ratio in automatic irrigation scheduling, while the authors of ref. [105] concluded that the evaluation of the impacts of the various local phenological and environmental factors is crucial since MDV represents water stress history rather than actual PWS. On the contrary, Ru [112] found that it could not be applied as indicator of water status, and suggested the use of signal intensity of MDS as a diagnosing index for more sensitive and reliable assessment.

3.4. Leaf Thickness

Sharon and Bravdo [167] showed that the continuous LT sensor-based drip irrigation treatment resulted in the highest yield and greatest water use efficiency. Similarly, Seelig [102] proved that using an automated irrigation system based on a LT sensor improves water use efficiency. Nevertheless, since the sensitivity of LT to changes in the water status of the leaves is sometimes inconsistent, this technique cannot always be reliable [100]. Furthermore, LT is affected by plant growth [69] and photosynthetic active radiation, where leaves developing in bright sunlight were shown to be substantially thicker than leaves that grew in the shade [181,182].

LT was studied for woody crops and herbaceous crops such as cowpea and common beans, and was shown to be an effective tool in the conservation of water when used in an irrigation schedule [102,183].

3.5. Water Potential

Regarding water potentials, midday SWP was shown to be a more accurate plant water stress indicator than soil water potential, predawn, and midday LWP [184–186], making it a reliable criterion for irrigation scheduling, particularly in fruit trees. It can be especially positive since its measurement can be automated [153]. The choice of which water potential indicator to use depends on the crop's anisohidric/isohydric behavior [33]. LWP fluctuates and is affected by environmental changes, putting into question its usefulness as an indicator for irrigation scheduling [29,33]. Nevertheless, this indicator can be used as a reference against which other water stress indicators can be tested due to its high sensitivity to an irrigation regime and its high correlation with fruit size [185].

Midday SWP was a good and sensitive indicator for irrigation scheduling in apples and nectarine [37,185]. Under mild water stress conditions, SWP was an accurate indicator in olives [187–189], citrus [190], and grapevines [191]. SWP was shown to be a direct measure of tree response to irrigation management in almonds, prunes, and walnuts [192]. In chestnut, LWP was used to assess water transpiration [193], and SWP was used as an indicator for smart irrigation [194]. In pistachio, SWP was considered a tool to manage an irrigation schedule [117], whereas, on the contrary, the isohydric behavior of grapefruit limited the use of SWP as an indicator of plant water status [160]. In cherry, Blanco [35,195] showed that SWP was the most reliable and stable water stress indicator compared to other physiological variables as it clearly detected irrigation changes and quantified water status. Nevertheless, due to the difficulty of its automated measurements, an estimation model was proposed based on other parameters [35].

3.6. Relative Water Content

RWC is a simple method used to determine PWS. Higher RWC in a plant indicates greater tolerance and survival under drought stress conditions [196,197]. Nevertheless, this method is labor-intensive and time-consuming, and is restricted to research purposes. It is rarely used as an indicator for irrigation scheduling commercially because it cannot be automated. Additionally, it was not found to be a sensitive measurement to highlight differences among irrigation treatments of nectarine due to the high variability among leaves [37]. On the other hand, in olive, RWC was shown to indicate the tree's water needs, prevent stress, and support irrigation scheduling [198].

3.7. Sap Flow

SF methods hold important advantages over other techniques in the measurement of transpiration since SF methods are easily automated, and therefore allow continuous records of plant water use with high time resolution over extended periods of time [199]. Studies have suggested using the ratio of SF as a potential trigger for when to irrigate [137,191,200]. Alternatively, measuring SF in irrigated plants and comparing results against representative control plants could be considered a successful approach to quantify the degree of water stress to avoid soil water limitations [73].

The correlation of SF to stomatal closure makes it a good indicator of water stress, as well as an estimate of transpiration rate and water loss [29,81], especially in woody crops [153,201]. This gives an idea of the amount of water to be added [29,202–204]. For instance, sensors were able to detect differences in both the timing and amount of water used by irrigated and non-irrigated crops [205,206]. Nevertheless, SF shows less sensitivity and reliability in detecting changes in PWS with respect to other indicators, such as maximum daily shrinkage [177].

Furthermore, flow is also very dependent on atmospheric conditions, and therefore shows great variability. This is why site-specific calibration procedures using reference models are needed to accurately determine transpiration through SF approaches considering changing meteorological conditions [207]. Cammalleri [208] suggested using micro-meteorological techniques (eddy covariance) with SF to effectively evaluate evapotranspiration to assess water stress. Moreover, the complex instrumentation and technical expertise required to interpret the results, as well as the need for constant calibration for each tree, limits its practical application [32,202].

The different methods used to measure SF have their own strengths and limitations. The sensors used in the stem heat balance method are rigid and of fixed size, not permitting stem growth. For this reason, their positions should be regularly changed to avoid stem strangulation during plant growth. Moreover, the heater band and the energy requirements become too large as the stem diameter thickens, leading to difficulties in calculating the stored heat. A new sensor was evaluated by Lascano [209], allowing better thermal contact between the plant stem and the temperature sensors. CHPM has been shown to have limitations regarding the measurements of low SF rates since the heat pulse may dissipate by conduction before it reaches the measurement point [202,210]. Therefore, accurate measurements of SF are possible only above a minimum threshold sap velocity. Testi and Villalobos [211] developed a calibrated average gradient method to measure the lower SF range. This method showed good results quantifying water consumption [203]. On the other hand, HRM is sensitive to the direction of SF, thus allowing the measurement of reverse flow and able to measure low rates of flow accurately [131,212]. However, substantial limitations were observed for high SF rates in highly conductive roots, and the method is considered less reliable at high flux densities [141,212]. The T-max method gives consistent measurements during the day instead of noisy measurements at night [138]. Nevertheless, the T-max method cannot measure low flow rates due to practical difficulties, and therefore presents limitations [131,138,213]. The ratio heat pulse method uses a novel low-cost 3D-printed SF gauge to measure transpiration, with the advantages of being easily replicated and deployed while allowing the same electronics to be used on plants of different shapes and stem diameters [79]. Furthermore, in contrast to the T-max method, this method can measure low flows under water stress conditions or at night [79,136]. The Sapflow+ method allows a nondestructive measurement of high, low, and reverse SFs, thermal wood properties, and water content of the sapwood based on thermodynamics [80,136]. On the other hand, some studies assumed using the thermal dissipation probe to measure SF to be a universal method applicable to all tree species, as long as the sensor and electrical power are identical, and the used probes are correctly inserted in the xylem [214–216]. Others showed that it should be calibrated depending on the individual species [141,199,201,217]. Furthermore, this method measures SF in part of the cross-section of the conductive organ, raising the occurrence of errors related to the estimation of the SF for the whole tree [141,216]. Additionally, its high electrical consumption can become a limitation in its practical use in the field since many repetitions are needed to scale up the measurements produced at the single tree level to a whole forest stand [141]. A synthesis of the use of sap flow methods concluded that although this method was widely used, it appeared to be consistently inaccurate, showed proportional bias, and generally underestimated sap flow, by 40% on average [131]. In an interest to lower heat consumption and save energy, the cyclic heating method was introduced while considering proper calibration and corrections [218]. The HFD method was shown to calculate SF at different depths in the sapwood and can distinguish high, low, and reverse flows [80,219]. The noise level is considered negligible, especially at low flux or zero flow densities [201]. Nevertheless, it can cause errors in estimations depending on the sap flux density, water content, and thermal characteristics of the wood [80,141,201].

In grapevine and lemon, SF was a sensitive approach to estimating plant water consumption and thus designing an irrigation program, since a minor change in SF, for instance, due to water stress, was shown to be an optional indicator for prompting irrigation [53,176]. Applying the transpiration method based on the calculation of SF in well-irrigated plants proved to be an effective method for the irrigation scheduling in olives and grapevines, but difficult to apply in commercial orchards due to limitations management [220]. Nadezhdina [148] defined a SF index, which can be automated and continuously recorded, and was shown to be sensitive when applied to apples. Muchena [202] used SF to study the sensitivity of apple rootstock to deficit irrigation. Nicolas [221] showed that SF measurements could be used as an indicator in the automation of an irrigation schedule. On the other hand, the authors of ref. [38] suggested monitoring leaf turgor, in combination with other plant physiological assessments such as SWP and MDS, may provide useful information to assess the response of rootstocks to drought stress.

3.8. Combination of Approaches

Since the effects of water quality are dynamic during a crop's growth, studies suggest the use of more than one method to enhance irrigation management. For example, the continuous SF measurements can be used in conjunction with other plant-based methods to give ground validation of other sensing approaches from areas where little information is available, thus forming a holistic monitoring strategy [208]. SF and MDS gave immediate and sensitive estimations in lemon trees [222] and in olives [223]. TDV and plant water potential were studied for apples [103], nectarines [175], and almonds [179]. In olives, the potential of the combined use of SWP, g_s, and TDV in irrigation scheduling was investigated [184]. In cherry, a correlation between SWP and TDV made it possible to obtain water deficit threshold values [224]. In grapevines, Shahidian [191] suggested the combination of SF and LWP measurements, whereas Malheiro [225] showed that the combined use SF and SDV revealed sensitivity to variable conditions of atmospheric demand and crop water status. On the other hand, also on grapevines, the authors of ref. [226] tested the applicability of automated sensors that measure LT and SF and compared them with SWP measurements with the aim of real-time monitoring of vine water stress. These studies reinforce the usefulness of combining plant-based measurement techniques in assessing water responses to variable environmental conditions.

4. Overview of Plant-Based Methodologies and Approaches in the Assessment of Water Status in Mediterranean Tree Crops

The following section comprises a series of works of literature that studied the above-mentioned plant-based methodologies and approaches in the assessment of water status and stress in Mediterranean crops. An extensive search through Google Scholar was conducted in June 2022 for articles dedicated to this field and published since 2012 to demonstrate the research trend in the last decade. The articles were related to the keywords representing the literature discussed in the first part, i.e., plant water status, plant water stress, stomatal conductance, leaf turgor, relative water content, stem diameter variation, water potential, and sap flow. Given the large number of retrieved papers, articles were selected based on three main criteria: (i) we selected journals with an impact factor > 2; (ii) the study should have used one or more approach or method as an aim to assess water stress and/or evaluate PWS; and (iii) the study must have taken place under a Mediterranean climate on fruit or nut tree crops (i.e., almond, apple, avocado, cherry, chestnut, citrus, fig, grapevine, hazelnut, loquat, nectarine, olive, peach, pear, persimmon, pistachio, plum, pomegranate, walnut). A total of 83 papers studying the previously detailed approaches and sensors on 19 Mediterranean crops were extracted, demonstrating those most used in the last 10 years.

4.1. Application of Sensors and Methods

The most commonly used approach in assessing water stress during the last 10 years was the measurement of LWP and SWP, followed by g_s, SF, SDV, leaf turgor, and RWC. SWP and LWP were widely measured by Scholander pressure chambers (46 studies), and to a much lesser extent by the novel pump-up pressure (4 studies), and once by a thermocouple psychrometer, in a study that compared water activity meters, which are types of psychrometers, to the Scholander pressure in measuring LWP in grapevines [124]. The widespread use of the Scholander pressure, despite its labor consuming and manual measurements, is likely due to the sensitive and accurate results. Nevertheless, as previously mentioned, these estimations should be used as a reference upon which other variables can be assessed. On the other hand, the measurement of g_s was conducted in 43 studies, 27 by means of

IRGAs, and 16 by porometers. The use of IRGAs in favor of porometers could be explained by the different species under study, since according to Toro [90], IRGAs give more accurate results in species with high g_s, whereas porometers would require calibration. Furthermore, SF (total 34 studies) was most predominantly measured by means of sensors based on the HPM (22 studies), and widely the CHPM (7), followed by the T-max (4). The second most common approach was the continuous heat method (9), particularly the thermal dissipation method, whereas the least frequent was the heat balance method (3). These observations can lead to the deduction that HPM is widely used since it gives accurate and sensitive measurements of SF and the sensors are more user-friendly, and also the obtained results are easier to interpret. Leaf turgor was uniquely measured by LPCPP (ZIM-probes), the sensor introduced in 2013 by the authors of ref. [100]. This finding proves that the introduction of a noninvasive sensor that continuously, automatically, and remotely records physiological variables generating easy-to-interpret results can successfully replace conventional and traditional sensors. Similarly, LVDTs (12 studies) were more common in recording SDVs than dendrometers (7 studies), since the first allows an automated and highly precise measurement. RWC was used in seven studies, particularly in the last 5 years. Figure 2 shows the application of the different sensors and methodologies from 2012 till 2022.

Table 2 shows the yearly trend of the application of the methods and sensors. It shows that PWS was common in the last decade, with a decline in 2014 and 2015, and a peak in 2019. It is clear that after the introduction of the ZIM-probe in 2013 by Zimmermann [100], it almost completely replaced the cell pressure probe as a continuous and non-invasive sensor to measure leaf turgor. Since 2018, the pump-up pressure gained popularity in measuring LWP and SWP, although Scholander pressure chambers remain the most widely used apparatus. To measure SF, the CHPM and the thermal dissipation method remained the most popular applied methods, whereas the novel Sapflow+, DHP, and SPHP were limited to the research study in which they were set up and tested.

Table 2. Approaches and sensors/methods to assess plant water status for the Mediterranean fruit and nut tree crops from 2012 to 2022.

Approaches and Sensors/Methods			Years											Total
			2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	
	Stomatal conductance (g_s)	Porometer	2	3	-	1	1	3	-	1	1	2	2	16
		Infrared gas ana-lyzer (IRGA)	2	1	-	-	5	2	3	6	4	4	-	27
	Leaf Turgor	Cell Pressure Probe	-	-	-	-	-	-	-	-	-	-	-	0
		LPCPP (ZIM-probe)	2	-	-	-	5	1	1	3	1	1	-	14
	Leaf Thickness (LT)	Micrometer	-	-	-	-	-	-	-	-	1	-	-	1
	Leaf Water Potential (LWP) and Stem Water Potential (SWP)	Thermocouple Psychrometer	-	1	-	-	-	-	-	-	-	-	-	1
		Scholander Pressure Chamber	2	7	-	2	7	4	4	8	3	6	3	46
		Pump up Pressure Chamber	-	-	-	-	-	-	1	-	2	1	-	4
	Stem Diameter Variation (SDV)	Dendrometer	-	1	-	1	-	2	-	1	-	2	-	7
		Linear Variable Differential Transformers (LVDT)	-	3	-	-	3	1	1	2	1	-	1	12
	Relative water Content (RWC)	Mass Weighing	1	-	-	-	-	1	-	3	2	-	-	7
	Sap Flow (SF)—Heat balance	Stem Heat Balance (SHB)	-	-	-	-	-	-	-	1	1	-	-	2
		Trunk Sector Heat Balance	-	1	-	-	-	-	-	-	-	-	-	1
	SF—Heat pulse	Compensation Heat Pulse Method (CHPM)	1	1	-	1	-	1	2	-	-	1	-	7
		Heat Ratio Method (HRM)	-	-	-	-	-	-	-	-	1	-	-	1
		T-max	-	2	-	-	-	-	-	-	1	1	-	4
		T_mRatio	-	-	-	-	-	-	-	-	-	-	-	0
		Sapflow+	-	-	4	-	-	-	-	-	-	-	-	4
		Single Probe Heat Pulse (SPHP)	-	-	-	-	-	5	-	-	-	-	-	5
		Dual Heat Pulse	-	-	1	-	-	-	-	-	-	-	-	1
	Continuous SF	Thermal Dissipation Probe	-	1	-	1	1	-	-	1	2	3	-	9
		Heat Field Deformation (HFD)	-	-	-	-	-	-	-	-	-	-	-	0
Total			10	21	5	6	22	20	12	26	20	21	6	

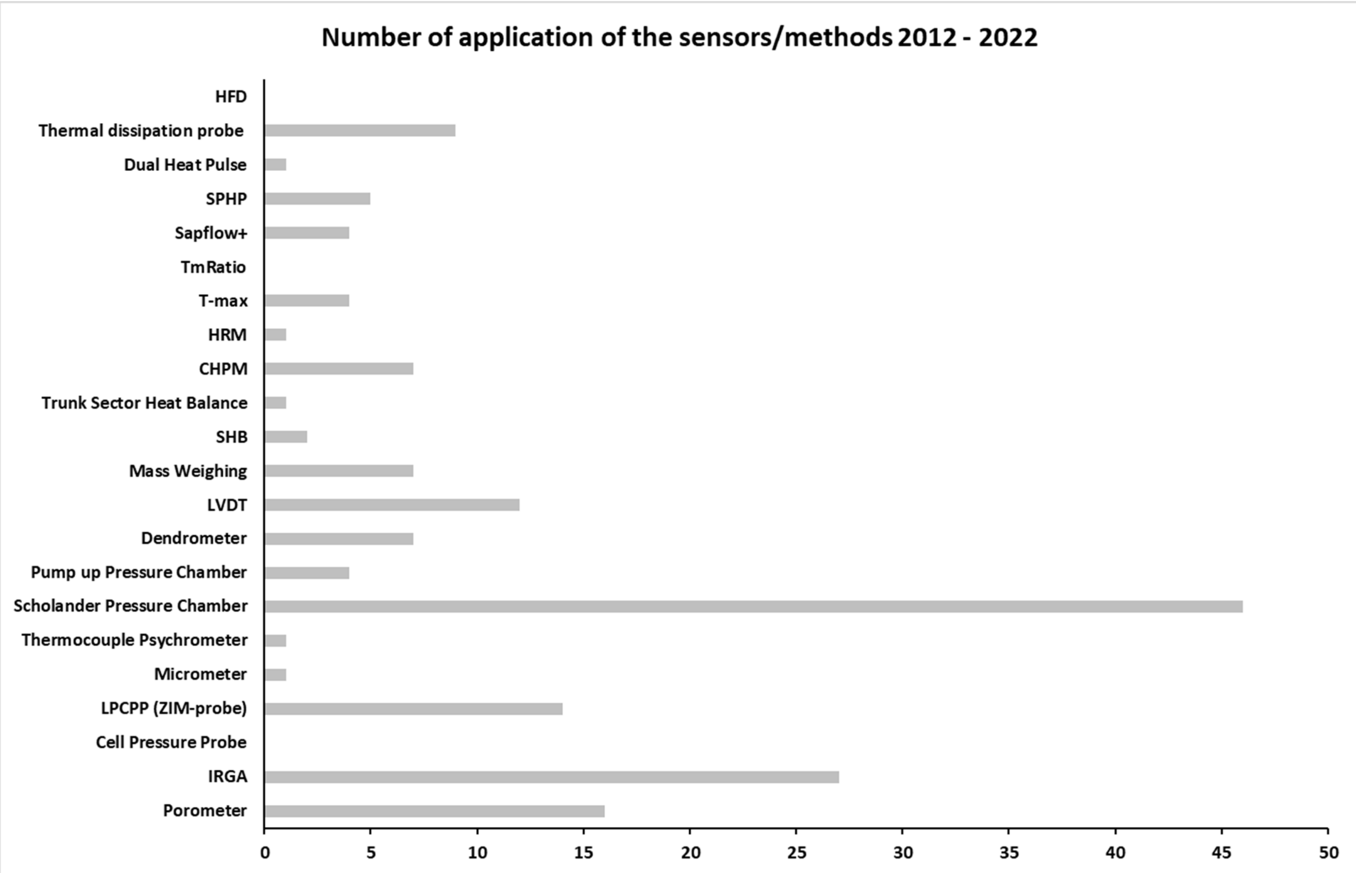

Figure 2. Number of applications of the different sensors and methodologies from 2012 till 2022 for Mediterranean fruit and nut tree crops.

4.2. Application Per Crop

The most studied crop is the olive, followed by grapevine, and citrus (Figure 3). This is principally justified by the economic importance of these crops and the menacing threats of the effects of climate change [227]. PWS in olive was assessed by measuring SF (25.6% of the total studies), followed by leaf turgor (23.2%), then g_s (21%), then SWP and LWP (18.6%), followed by SDV (9.3%), and finally RWC (2.3%). In grapevine, the two most common approaches to assess PWS were SWP and LWP (33.3%) by means of Scholander pressure (24.2% of the total studies), pump-up pressure (6.1%), and least, by a thermocouple psychrometer (3%), followed by g_s (30.3%), 24.2% by means of IRGA and 6.1% by means of a porometer. The prevalent method to measure SF was the thermal dissipation method (21.2%), whereas the heat balance method, the CHPM, the T-Max, and the DHPM were each used in one study, respectively. In parallel, three studies applied SDV to assess water stress. In citrus, the prevalent approach was SWP and LWP using a Scholander pressure chamber, followed by SF using the heat pulse method (one study for each respectively: CHPM, T-Max, Sapflow+, SPHP) and thermal dissipation (one study). In addition, g_s was measured in three studies by IRGA and once by means of a porometer.

Table 3 shows the type of sensor or method applied to assess PWS per crop. Of note, g_s was measured by means of a porometer in fig, persimmon, and plum, and by means of an IRGA in loquat and pear. Both methods were applied on almond, cherry, nectarine, peach, pomegranate, citrus, grapevine, and olive. The ZIM-probe was used to measure leaf turgor in olive, almond, grapevine, nectarine, and persimmon. The Scholander pressure chamber was widely used in almond, cherry, citrus, grapevine, loquat, nectarine, olive, peach, pear, persimmon, pistachio, plum, and pomegranate. The pump-up pressure was used once in each of grapevine, chestnut, and olive, while the psychrometer was applied once on grapevine. Dendrometers to measure SDV were used on apple, nectarine, olive, and pomegranate, whereas the more popular LDVTs were applied on apple, avocado, cherry, fig, grapevine, nectarine, and peach. On the other hand, RWC was common on grapevine, nectarine, olive, peach, and pomegranate. As far as the SF techniques were concerned, SHB was used once on apple and once on grapevine, while the trunk HB was used once on cherry. CHPM was used on almond, citrus, grapevine, and olive. HRM was used only once on apple, whereas T-Max was applied once on each of almond, fig, and olive. Sapflow+ was tested once on each of almond, citrus, fig, and olive, while SPHP was experimented once on each of almond, citrus, olive, pear, and walnut. The dual heat pulse method was tested on grapevine. The thermal dissipation method was applied on citrus, hazelnut, grapevine, and olive.

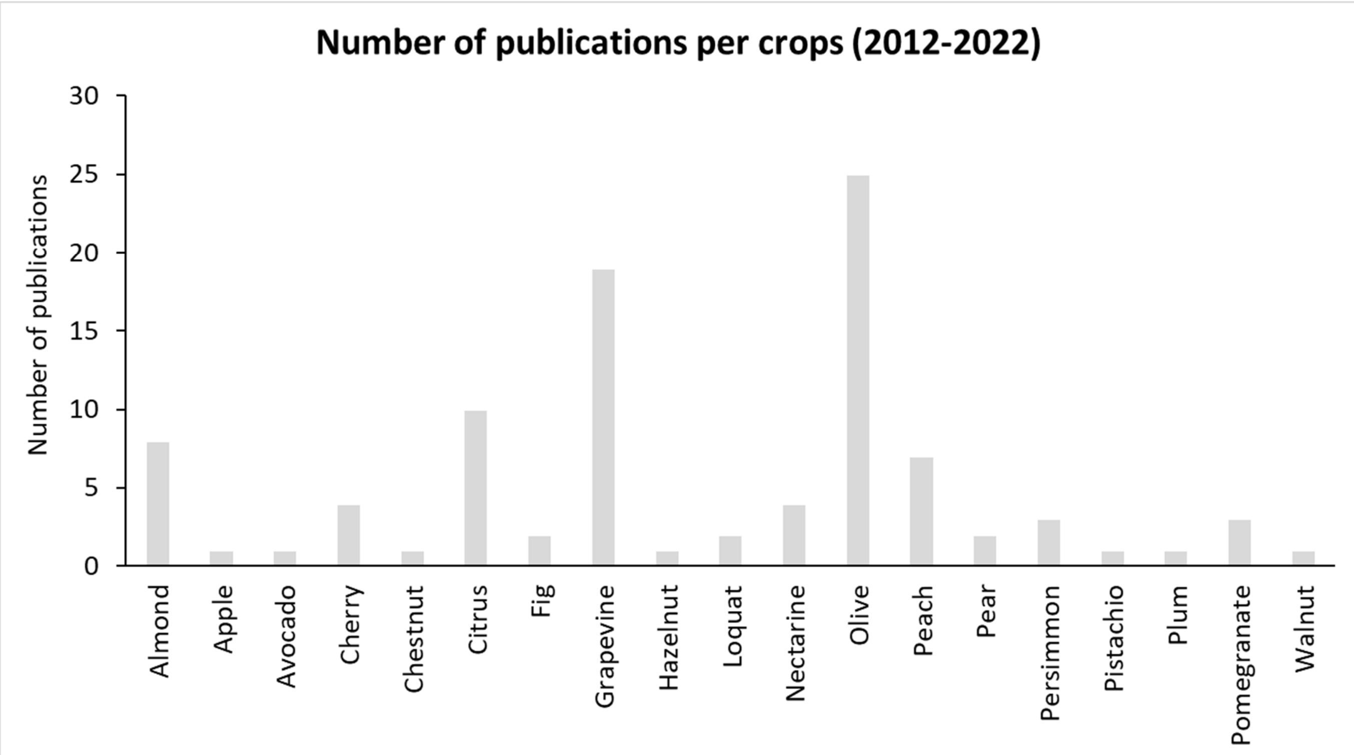

Figure 3. Number of publications studying the application of the different sensors and methodologies from 2012 till 2022 per Mediterranean fruit and nut tree crops from a total of 83 references.

4.3. Application Per Country

Figure 4 shows the countries where PWS was studied on the fruit and nut trees under the Mediterranean climate. The most active country in this field of research is by far Spain, having published 48 papers testing 13 different sensors and methods. Behind it comes Italy with 11 publications on 10 sensors and methods, Portugal, and California (USA) with 5 and 4 publications, respectively, Tunisia, Israel, and Iran with 3 publications each, followed by South Australia with 2 publications, and finally Greece, Morocco, Oregon (USA), and South Africa with 1 publication each. This significant interest in research in Spain notably is attributed to the government's dedication to address climate change impact issues through, first, their incorporation into the Spanish water legislation by making compulsory their consideration in national water management plans and policies [228,229], and second, promoting the implementation of new technologies and irrigation infrastructures that are aimed for young and educated farmers, but can be equally and easily accessed by older farmers with low education backgrounds, as stated by the authors of ref. [230]. Italy was shown to be the second leading country. According to the authors of ref. [231], the previous governments and political parties were divergent regarding environment issues;

nevertheless, the newly emerging parties highlighted the importance of these impacts and concentrated on the implementation of up-to-date national strategies. The lesser interest in other countries is attributed to political conflicts and lack of a unified vision faced by policymakers when defining national and international strategies for addressing climate change [232].

Table 3. Approaches and sensors/methods to assess plant water status from 2012 to 2022 per Mediterranean fruit and nut tree crops.

	Approaches and Sensors/Methods																					
	Stomatal Conductance g_s		Leaf Turgor		Leaf Thickness LT	Leaf and Stem Water Potential (LWP and SWP)			Stem Diameter Variation (SDV)		Relative Water Content (RWC)	Sap Flow (SF) Heat Balance		SF Heat Pulse							Continuous SF	
	Porometer	**Infrared Gas Analyzer (IRGA)**	**Cell Pressure Probe**	**Cell Pressure Probe LPCPP**	**Micrometer**	**Thermocouple Psychrometer**	**Scholander Pressure Chamber**	**Pump up Pressure Chamber**	**Dendrometer**	**Linear Variable Differential Transformers (LVDT)**	**Mass Weighing**	**Stem Heat Balance (SHB)**	**Trunk Sector Heat Balance**	**Compensation Heat Pulse Method (CHPM)**	**Heat Ratio Method (HRM)**	**T-max**	**T_mRatio**	**Sapflow+**	**Single Probe Heat Pulse (SPHP)**	**Dual Heat Pulse**	**Thermal Dissipation Probe**	**Heat Field Deformation (HFD)**
Almond	1	1	-	1	-	-	5	-	1	1	-	-	-	1	-	1	-	1	1	-	-	-
Apple	-	-	-	-	-	-	-	-	-	-	-	1	-	-	1	-	-	-	-	-	-	-
Avocado	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-
Cherry	1	2	-	-	-	-	4	-	-	3	-	-	1	-	-	-	-	-	-	-	-	-
Chestnut	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Citrus	1	3	-	-	-	-	6	-	-	1	-	-	-	1	-	1	-	1	1	-	1	-
Fig	1	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	1	-	-	-	-
Grapevine	2	8	-	1	1	1	8	2	-	3	-	1	-	1	-	1	-	-	-	1	3	-
Hazelnut	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-
Loquat	-	1	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nectarine	2	1	-	1	-	-	2	-	1	1	1	-	-	-	-	-	-	-	-	-	-	-
Olive	2	7	-	10	-	-	7	1	4	-	1	-	-	4	-	1	-	1	1	-	4	-
Peach	2	2	-	-	-	-	4	-	-	2	2	-	-	-	-	-	-	-	-	-	-	-
Pear	-	1	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-
Persimmon	1	-	-	1	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pistachio	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Plum	1	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pomegranate	2	1	-	-	-	-	3	-	1	-	2	-	-	-	-	-	-	-	-	-	-	-
Walnut	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-
Total	16	27	0	14	1	1	46	4	7	12	7	2	1	7	1	4	0	4	5	1	9	0

Appendix A includes a table representing all references over the last ten years on plant-based methodologies and approaches in the assessment of water status in Mediterranean tree crops, along with the main aim or scope of work of each.

Appendix B contains a list of 83 references studies over the last decade on plant-based methodologies and approaches in the assessment of water status in Mediterranean tree crops.

Appendix C consists of a map that represents the geographical distribution of the 83 references of the last decade of the application of the different sensors and methodologies for Mediterranean fruit and tree crops.

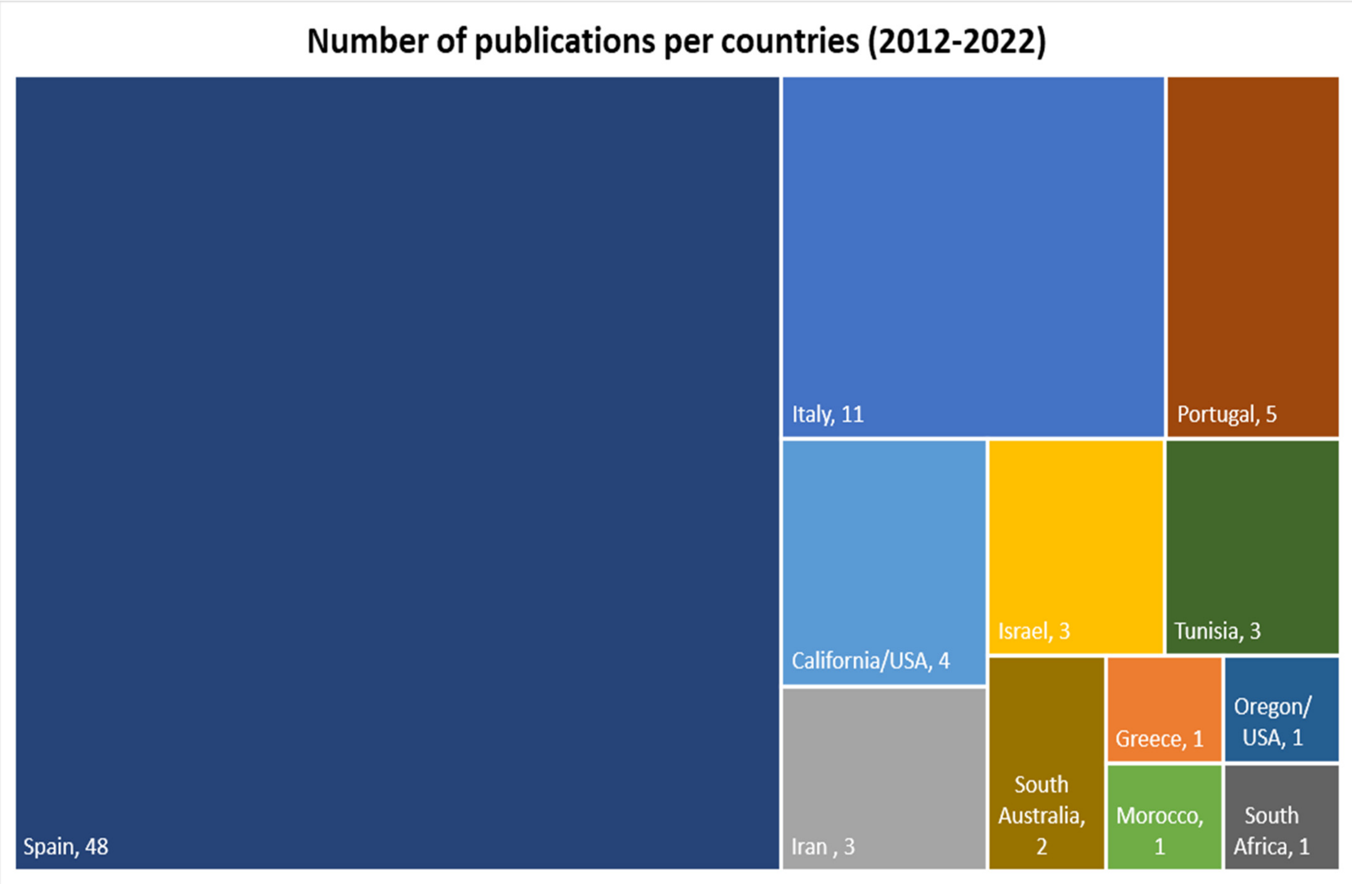

Figure 4. Number of publications per country of the application of the different sensors and methodologies from 2012 till 2022 for Mediterranean fruit and tree crops.

5. Conclusions

Improving irrigation management and scheduling in agriculture by saving water while increasing crop yield quantity and quality is crucial in the handling of water scarcity caused by climate change. The choice of which plant-based approach to use and which method to follow to assess water status depends on the crop and its relative sensitivity and physiological adaptation to water deficits. Standardization of the methods applied is a necessity, but can be limited by the species-specific response, and the approach that is valid for one crop can be inapplicable for others. Since every method and sensor has its conveniences and limitations, combining two or more approaches could give a more representative model of water status and crop stress conditions, but more studies should be done to prove the applicability of combined methods in the establishment of an effective irrigation schedule [226]. Moreover, since plant-based approaches are sensitive to any slight modification in the surrounding environment, especially changes in meteorological conditions, the development of a protocol for assessing PWS by considering several indices in real-time basis is suggested. In fact, research is constantly done to provide modern and user-friendly technologies that allow data to be automatically and remotely monitored and accessible through the cloud across platforms, in order to help implement irrigation strategies according to actual plant responses [233,234], providing readily available measurements to commercial growers. This whole sequence thus facilitates the creation of an appropriate crop irrigation schedule based on real plants' water needs as a water saving strategy.

On the other hand, the survey and descriptive analysis of 83 publications dedicated to PWS assessment in the Mediterranean climate on the most common fruit and nut tree crops highlighted the research done in the last decade in this area of study. It showed that the new and improved techniques, methodologies, and sensors are able to replace the conventional methods given their ease of application and sensitivity. For instance, the ZIM-probe became the sole sensor used to measure leaf turgor since its introduction [93], while other sensors, namely some measuring SF [79–81], remained limited for research purposes. Furthermore, it demonstrated that some crops such as olives, grapevines, and citrus are more subject to study than others, notably for their economic value in the region and the urgency to save them from the threat of increasing drought [227]. Additionally, the analysis highlighted the active involvement of certain countries in such research, with Spain leading by far, mainly due to the government's commitment to fight climate change [228–230].

Nevertheless, adding to these findings, data communication dedicated to PWS assessment, especially under the Mediterranean climate, needs to be more widespread and common. For this, science needs to make a double effort by improving the technology, the sensor sensitivity, and the species specificity. The different approaches should be easy to apply, measurements simple to read, and results clear to understand. Additionally, the updated sensors and technologies need to be available at a reasonable cost, making them more convenient and accessible for commercial production.

The present semi-systematic review and the observations deduced from the survey conducted in this work will serve as a reference for the past studies and a guide for future research in the assessment of PWS. This work is expected to motivate scientists to construct more efficient decision support systems that can be easily applied by farmers on-field to enable the early detection of water stress in crops, consequently preventing irreversible damage and preserving yield whilst conserving water.

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Appendix A. Table Representing All Studies over the Last Ten Years on Plant-Based Methodologies and Approaches in the Assessment of Water Status in Mediterranean Tree Crops

Approach	Sensors/Method	Reference	Year	Crop	Country	Scope of Work
Stomatal conductance (g_s)	Porometer	[235]	2013	Citrus	Spain	Comparing thermography with Stem Water Potential (SWP) and g_s
				Persimmon		
		[109]	2013	Cherry	Spain	Evaluation of Maximum Daily Shrinkage (MDS): g_s, Leaf Water Potential (LWP), Sap Flow (SF)
		[236]	2017	Olive	Spain	SF to monitor g_s oscillations
		[128]	2012	Pomegranate	Spain	Plant water relations in response to water stress

Approach	Sensors/Method	Reference	Year	Crop	Country	Scope of Work
		[237]	2022	Almond Peach	Spain	Physiological responses under semi-arid conditions
		[37]	2019	Nectarine	South Australia	Combined leaf and water sensing for continuous water stress detection
		[191]	2016	Grapevine	Portugal	LWP and SF as water stress indicators
		[33]	2017	Plum Grapevine	Portugal	Plant Water Status (PWS) indicators for irrigation scheduling
		[147]	2021	Pomegranate Nectarine	California/USA	Evaluating Trunk Relative Water Content (TRWC) compared to commercial sensors
		[127]	2020	Fig	Tunisia	Recovery from water stress
		[238]	2012	Olive	Spain	Effect of water stress on water relations
		[158]	2015	Peach	Iran	Gas exchange under water deficit
	Infrared gas ana-lyzer (IRGA)	[239]	2018	Loquat	Spain	Gas exchange under water deficit
		[118]	2013	Olive	Spain	LWP and g_s response to water stress
		[240]	2017	Pomegranate	Iran	Responses to water stress
		[156]	2016	Grapevine	Spain	Cultivars stomatal behavior under water stress
		[190]	2020	Citrus	Iran	Monitoring feedback mechanism between LWP and g_s
		[86]	2021	Citrus	Israel	Testing effect of drought
		[161]	2012	Grapevine	California/USA	LWP and g_s effect on water use
		[241]	2012	Grapevine	Portugal	Stomatal response to water deficit
		[90]	2019	Grapevine	Spain	Comparing porometer to Infrared gas analyzer (IRGA)
		[152]	2016	Olive	Spain	Relationship between g_s and sap flux
		[113]	2017	Olive	Spain	Effect of water deficit on Trunk Diameter Variation (TDV) and g_s
		[242]	2018	Olive	Spain	Simulating g_s based on SF
		[189]	2020	Olive	Morocco	LWP, g_s, and leaf turgor behavior under water deficit
		[160]	2021	Citrus	Spain	g_s as water stress indicator for irrigation scheduling
		[243]	2019	Peach	Tunisia	Effect of irrigation strategy
		[157]	2021	Pear	Israel	Stomatal regulation under drought
		[244]	2021	Grapevine	Italy	Crop water stress index
		[35]	2018	Cherry	Spain	Plant water indicators (SWP, g_s, MDS) for irrigation management
		[245]	2019	Grapevine	Spain	Water use efficiency at different water status
		[36]	2019	Grapevine	California/USA	Assessing the most sensitive grapevine plant water stress indicator (MDS, WP, sap flow, g_s)
		[246]	2020	Peach	Spain	Responses to water stress

Approach	Sensors/Method	Reference	Year	Crop	Country	Scope of Work
		[247]	2019	Cherry	Italy	Water relations (SWP, LWP, g_s) affected by rootstock vigor
		[92]	2016	Olive	Spain	Relationship between g_s and leaf turgor under water stress
				Almond		
				Grapevine		
		[168]	2019	Olive	Spain	Sensitivity of leaf turgor to g_s and plant water stress
		[248]	2020	Nectarine	Spain	Effect of drought on g_s
Leaf Turgor	Cell Pressure Probe	-	-	-	-	-
	Cell Pressure Probe LPCPP (ZIM-probe)	[38]	2017	Persimmon	Spain	Assessing ZIM-probe for water stress and irrigation scheduling
		[163]	2016	Olive	Spain	Irrigation scheduling from leaf turgor in olive
		[162]	2018	Olive	Spain	Irrigation scheduling from leaf turgor in olive
		[165]	2016	Olive	Tunisia	Early water stress detection
		[249]	2012	Olive	Spain	Theoretical application of leaf turgor pressure Pc
		[189]	2020	Olive	Morocco	LWP, g_s, and leaf turgor behavior under water deficit
		[92]	2016	Olive	Spain	Relationship between g_s and leaf turgor under stress
				Almond		
				Grapevine		
		[168]	2019	Olive	Spain	Sensitivity of leaf turgor to g_s and plant water stress
		[164]	2012	Olive	Spain	SF and leaf turgor for irrigation scheduling and better understanding of water stress
		[188]	2021	Olive	Italy	Detecting mild water stress in olive with multiple plant-based continuous sensors
		[39]	2016	Olive	Italy	Online system based on pressure probes for irrigation scheduling
		[37]	2019	Nectarine	South Australia	Combined leaf and water sensing for continuous water stress detection
Leaf Thickness (LT)	Micrometer/ Linear Variable Differential Transformers (LVDT)	-	-	-	-	-
LWP and SWP	Thermocouple Psychrometer	[124]	2013	Grapevine	Spain	LWP (comparing water activity meters to Scholander pressure)
	Scholander Pressure Chamber	[235]	2013	Citrus	Spain	Comparing thermography with SWP and g_s
				Persimmon		
		[156]	2016	Grapevine	Spain	Cultivars stomatal behavior under water stress
		[118]	2013	Olive	Spain	LWP and g_s response to water stress
		[86]	2021	Citrus	Israel	Test effect of drought
		[190]	2020	Citrus	Iran	Monitoring feedback mechanism between LWP and g_s
		[238]	2012	Olive	Spain	Effect of water stress on water relations
		[250]	2013	Almond	Spain	MDS in irrigation scheduling
		[117]	2016	Pistachio	Spain	SWP for irrigation scheduling

Approach	Sensors/Method	Reference	Year	Crop	Country	Scope of Work
		[109]	2013	Cherry	Spain	Evaluation of MDS (g_s, LWP, SF)
		[251]	2018	Loquat	Spain	Monitor PWS by SWP to test irrigation effect
		[92]	2016	Olive Almond Grapevine	Spain	Relationship between g_s and leaf turgor under water stress
		[35]	2018	Cherry	Spain	Plant water indicators (SWP, g_s, MDS) for irrigation management
		[81]	2017	Olive	Spain	SF to monitor g_s oscillations
		[164]	2012	Pomegranate	Spain	Plant water relations in response to water stress
		[252]	2016	Grapevine	Spain	MDS and SWP for irrigation scheduling
		[37]	2019	Nectarine	South Australia	Combined leaf and water sensing for continuous water stress detection
		[147]	2021	Pomegranate Nectarine	California/USA	Evaluating tree RWC compared to commercial sensors
		[247]	2019	Cherry	Italy	Water relations (SWP, LWP, g_s) affected by rootstock vigor
		[36]	2019	Grapevine	Italy	Assessing the most sensitive grapevine plant water stress indicator (MDS, WP, Sap flow, g_s)
		[191]	2016	Grapevine	Portugal	LWP and SF as water stress indicators
		[33]	2017	Plum Grapevine	Portugal	PWS indicators for irrigation scheduling
		[39]	2016	Olive	Italy	Online system based on pressure probes for irrigation scheduling
		[253]	2020	Grapevine	California/USA	Spatial variability on plant water status
		[157]	2021	Pear	Israel	Stomatal regulation under drought
		[240]	2017	Pomegranate	Iran	Responses to water stress
		[246]	2020	Peach	Spain	Responses to water stress
		[195]	2019	Cherry	Spain	Effect of irrigation on plant water relations
		[254]	2021	Citrus	Italy	Adaptation and identification of water stress
		[125]	2019	Grapevine	Oregon/USA	Re-evaluating pressure chamber for water status
		[255]	2018	Olive	Spain	Effect of cold on water status (SWP)
		[111]	2019	Almond	Spain	Limitation of trunk variations in irrigation scheduling (MDS not useful, trunk growth rate more sensitive)
		[119]	2015	Peach	Spain	Seasonal pattern of SWP
		[188]	2021	Olive	Italy	Detecting mild water stress in olive with multiple plant-based continuous sensors
		[239]	2018	Loquat	Spain	Gas exchange under water deficit
		[243]	2019	Peach	Tunisia	Effect of irrigation strategy

Approach	Sensors/Method	Reference	Year	Crop	Country	Scope of Work
		[256]	2016	Citrus	Spain	Effect of long-term water deficit
		[257]	2013	Persimmon	Spain	Effect of water stress on fruit crops
		[258]	2022	Citrus	Spain	Effect of water stress
		[259]	2013	Almond	South Australia	Compare SF and water stress (SWP)
		[237]	2022	Peach Almond	Spain	Physiological responses under semi-arid conditions
	Pump up Pressure Chamber	[189]	2020	Olive	Morocco	LWP, g_s, and leaf turgor behavior under water deficit
		[194]	2018	Chestnut	Portugal	Relating plant and soil water content
		[244]	2021	Grapevine	Italy	Crop water stress index
Stem Diameter Variation (SDV)	Dendrometer	[147]	2021	Pomegranate Nectarine	California/USA	Evaluating TRWC compared to commercial sensors
		[260]	2013	Olive	Spain	Assessing water stress from STV and SF
		[111]	2019	Almond	Spain	Limitation of trunk variations in irrigation scheduling (MDS not useful, trunk growth rate more sensitive)
		[81]	2017	Olive	Spain	SDV and SF to monitor g_s oscillations
		[113]	2017	Olive	Spain	Effect of water deficit on TDV and gs
		[223]	2015	Olive	Italy	Usefulness of stress sensors
	LVDT	[35]	2018	Cherry	Spain	Plant water indicators (SWP, g_s, MDS) for irrigation management
		[195]	2019	Cherry	Spain	Effect of irrigation on plant water relations
		[261]	2016	Nectarine	Spain	Sensitivity of trunk variations to water stress
		[36]	2019	Grapevine	Italy	Assessing the most sensitive grapevine plant water stress indicator (MDS, Water Potential WP, SF, g_s)
		[225]	2020	Grapevine	Portugal	Combination of SF and TDV to study water status
		[262]	2016	Peach	Spain	Irrigation scheduling based on MDS
		[21]	2017	Peach	Spain	Irrigation scheduling based on MDS
		[252]	2016	Grapevine	Spain	MDS and SWP for irrigation scheduling
		[258]	2022	Citrus	Spain	Effect of water stress
		[105]	2013	Avocado	Israel	Patterns of MDV
		[250]	2013	Almond	Spain	MDS in irrigation scheduling
		[109]	2013	Cherry	Spain	Evaluation of MDS (g_s, LWP, SF)
Relative Water Content (RWC)	Mass Weighing	[37]	2019	Nectarine	South Australia	Combined leaf and water sensing for continuous water stress detection
		[240]	2017	Pomegranate	Iran	Responses to water stress
		[198]	2019	Olive	Spain	Irrigation decision support based on RWC
		[243]	2019	Peach	Tunisia	Effect of irrigation strategy
		[128]	2012	Pomegranate	Spain	Plant water relations in response to water stress

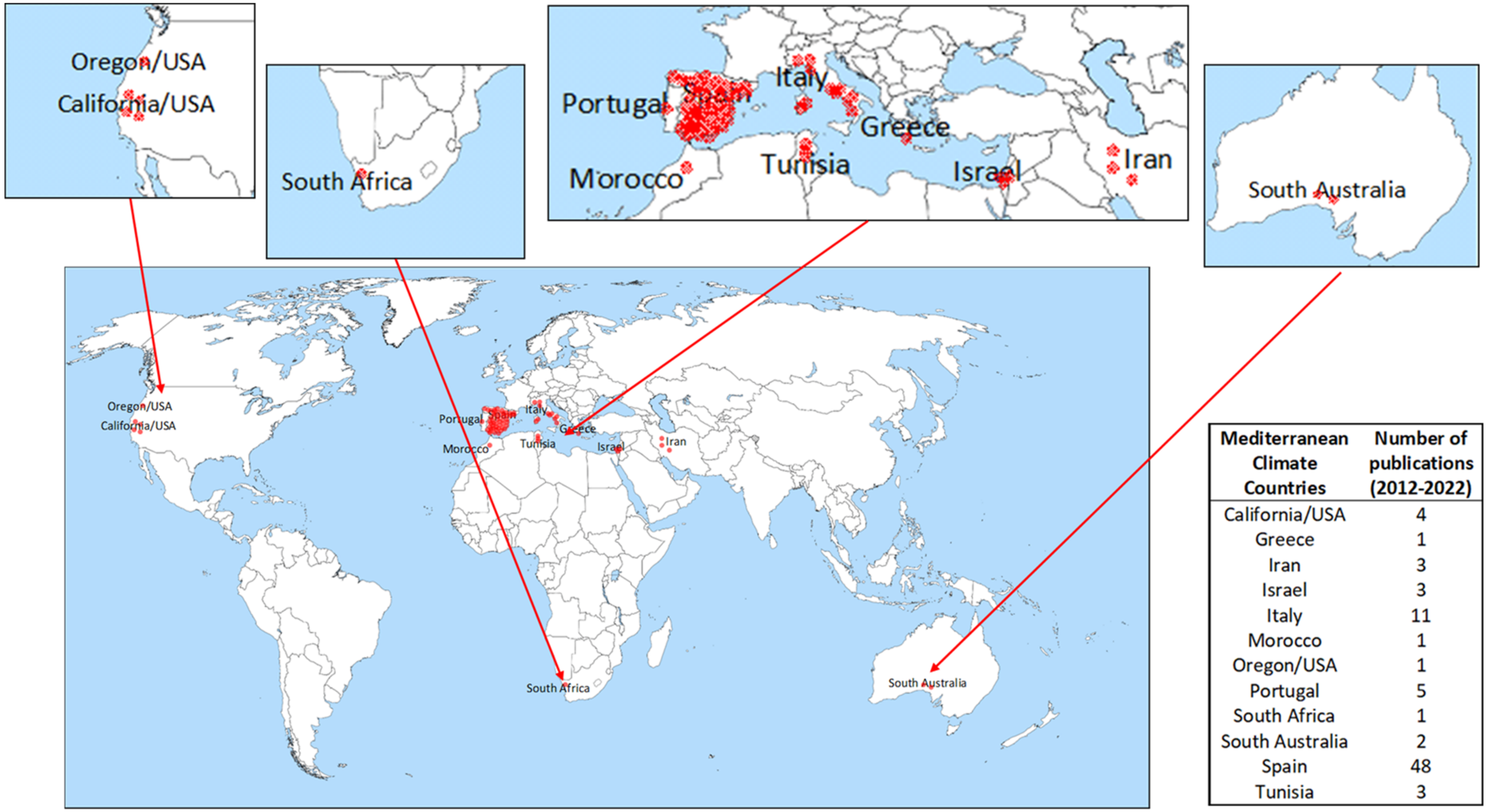
Approach	Sensors/Method	Reference	Year	Crop	Country	Scope of Work
SF—Heat balance	Stem Heat Balance (SHB)	[127]	2020	Fig	Tunisia	Recovery from water stress
		[246]	2020	Peach	Spain	Responses to water stress
		[36]	2019	Grapevine	Italy	Assessing the most sensitive grapevine plant water stress indicator (MDS, WP, SF)
		[202]	2020	Apple	South Africa	The use of SF techniques to estimate apple tree water use under conditions of water deficit and recovery
	Trunk Sector Heat Balance	[109]	2013	Cherry	Spain	Evaluation of MDS (g_s, LWP, SF)
SF—Heat pulse	Compensation Heat Pulse Method (CHPM)	[164]	2012	Olive	Spain	SF and leaf turgor for irrigation scheduling and better understanding of water stress
		[81]	2017	Olive	Spain	SF to monitor g_s oscillations
		[263]	2015	Olive	Spain	Using SF to estimate net assimilation
		[235]	2013	Citrus	Spain	SF—heat pulse for plant water stress detection
		[242]	2018	Olive	Spain	Simulate g_s based on SF
		[203]	2021	Grapevine	Spain	Water needs in vineyards based on SF
		[206]	2018	Almond	Spain	SF to estimate transpiration
	Heat Ratio Method (HRM)	[202]	2020	Apple	South Africa	The use of SF techniques to estimate apple tree water use under conditions of water deficit and recovery
	T-max	[260]	2013	Olive	Spain	Assessing water stress from TDV and SF
		[259]	2013	Almond	South Australia	Comparing SF and water stress (SWP)
		[226]	2021	Grapevine	Italy	Automated monitoring of plant water stress
		[254]	2021	Citrus	Italy	Adaptation and identification of water stress
	T_mRatio	-	-	-	-	-
	Sapflow+	[264]	2014	Olive	Spain	Comparing Sapflow+, T-max, HRM, and CHPM
				Fig		
				Almond		
				Citrus		
	Single Probe Heat Pulse (SPHP)	[81]	2017	Olive	Spain	Presenting, testing, and assessing the potential of SPHP method for monitoring sap velocity
				Citrus		
				Pear		
				Walnut		
				Almond		
	Dual Heat Pulse	[82]	2014	Grapevine	California/USA	New method for SF
Continuous SF	Thermal Dissipation Probe	[225]	2020	Grapevine	Portugal	Linking SF and trunk diameter measurements to assess water dynamics
		[188]	2021	Olive	Italy	Detecting mild water stress in olive with multiple plant-based continuous sensors
		[191]	2016	Grapevine	Portugal	LWP and SF as water stress indicators
		[208]	2013	Olive	Italy	SF and eddy covariance for water status assessment
		[86]	2021	Citrus	Israel	Testing effect of drought

Approach	Sensors/Method	Reference	Year	Crop	Country	Scope of Work
		[204]	2021	Olive	Greece	Crop water requirements based on SF
		[223]	2015	Olive	Italy	Usefulness of stress sensors
		[207]	2019	Grapevine	Italy	Recalibration of thermal dissipation probe
		[265]	2020	Hazelnut	Italy	Calibrating TDM for better irrigation management
	Heat Field Deformation (HFD)	-	-	-	-	-

Appendix B. Table Representing 83 References Studies over the Last Decade on Plant-Based Methodologies and Approaches in the Assessment of Water Status in Mediterranean Tree Crops

Abdelfattah et al., 2013	Abrisqueta et al., 2015	Aissaoui et al., 2016	Alizadeh et al., 2021
Ammar et al., 2020	Badal et al., 2013	Ballester et al., 2013	Ballester et al., 2018
Blanco et al., 2019	Blanco-Cipollone et al., 2017	Bota et al., 2016	Cammalleri et al., 2013
Centeno et al., 2018	Cocozza et al., 2015	Conesa et al., 2016	Conesa et al., 2020
Costa et al., 2012	Cuevas et al., 2013	Cuevas et al., 2013	De la rosa et al., 2016
De Oliveira et al., 2021	Dell'Amico et al., 2012	Ehrenberger et al., 2012	El yamani et al., 2020
El yamani et al., 2020	El yamani et al., 2020	Fuentes et al., 2013	Fuentes et al., 2013
Gasque et al., 2016	Guizani et al., 2019	Guizani et al., 2019	Guizani et al., 2019
Hernandez-santana, 2016	Hernandez-santana et al., 2017	Hernandez-santana et al., 2018	Jamshidi et al., 2020
Jiménez et al., 2020	Kokkotos et al., 2021	Levin, 2019	López-Bernal et al., 2014
López-bernal et al., 2015	López-bernal et al., 2017	López-López et al., 2018	Malheiro et al., 2020
Mancha et al., 2021	Marino et al., 2016	Marino et al., 2021	Martinez et al., 2020
Martínez-Gimeno, 2017	Martín-palomo et al., 2019	Memmi et al., 2015	Mirás-avalos et al., 2016
Morandi et al., 2019	Mota et al., 2018	Muchena et al., 2020	Padilla-Díaz, 2016
Pagán et al., 2022	Pasqualotto et al., 2020	Paudel et al., 2021	Pearsall et al., 2014
Pourghayoumi et al., 2017	Puerto et al., 2013	Rahmati et al., 2015	Rana et al., 2019
Reig et al., 2022	Rodríguez et al., 2012	Rodriguez-dominguez et al., 2012	Rodriguez-dominguez et al., 2016
Rodriguez-dominguez et al., 2019	Romero-trigueros et al., 2021	Saitta et al., 2021	Scalisi et al., 2019
Shahidian et al., 2016	Silber et al., 2013	Stellfeldt et al., 2018	Toro et al., 2019
Torres et al., 2019	Torres-Ruiz et al., 2013	Tortosa et al., 2019	Tuccio et al., 2019
Wagner et al., 2021	William et al., 2012	Yu et al., 2020	

Appendix C. World Map Representing the Number of Publications per Counties from 2012 till 2022 of the Application of the Different Sensors and Methodologies for Mediterranean Fruit and Tree Crops



Mediterranean Climate Countries	Number of publications (2012-2022)
California/USA	4
Greece	1
Iran	3
Israel	3
Italy	11
Morocco	1
Oregon/USA	1
Portugal	5
South Africa	1
South Australia	2
Spain	48
Tunisia	3

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