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# Water stress indicators in citrus, olive and apple trees: A review

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## Abstract

Agriculture is grappling with water scarcity, leading to diminished crop yields, economic challenges, environmental degradation, and threats to food security. The future of agriculture hinges on the implementation of sustainable water resource management and adaptation strategies. Specifically, in arid regions, the adoption of water-efficient irrigation practices is crucial for fruit growers. This approach not only helps in conserving water but also reduces costs and ensures the vitality of orchards. The cultivation of fruit trees, especially in water-stressed areas, demands meticulous irrigation management for survival. Growers play a key role in identifying stress indicators that serve as crucial markers for monitoring tree health. Proactively addressing these indicators enables growers to maintain healthier trees, resulting in higher yields. Identifying and understanding fruit tree stress indicators play a pivotal role in enhancing orchard management practices, ultimately contributing to increased yields, cost reduction, and the promotion of sustainability. This review evaluates the effectiveness of stress indicators in gauging water stress levels. It delves into the multifaceted impacts of water scarcity on agriculture and underscores the recommendation for water-efficient irrigation practices to counteract fluctuations in water availability. In environments facing water scarcity, vigilant irrigation management coupled with the identification of stress indicators strengthens the resilience and productivity of fruit tree agriculture. This study contributes valuable insights to the ongoing discourse on sustainable horticulture in the face of a changing world.

**Key words:** Hydric stress, morphological features, physiological features, biochemical features

## Introduction

Fruit trees are vital in sustaining human life by generating oxygen, cleansing the air, and providing nourishment. Fruit trees, in particular, serve a dual purpose by yielding edible fruits that are not only rich in water, vitamins, trace elements, and fiber but also packed with essential phytochemicals beneficial to human health, such as vitamin C, vitamin B, potassium, phosphorous, enzymes, and various other elements (Aruoma *et al.*, 2012). These phytochemicals reduce certain diseases (Uylaşer and Yildiz, 2014).

In global agriculture, where more than two-thirds of the world's freshwater is allocated (Chai *et al.*, 2016), the need for efficient water management in crop cultivation cannot be overstated. As elaborated by Fernandez (2017), precision irrigation strives to enhance crop water efficiency by meticulously selecting irrigation systems, strategies, scheduling methods, and production targets.

The global water shortage, as Corell *et al.* (2019) emphasised, underscores the urgency of developing indicators to manage water stress efficiently. Effective irrigation strategies are pivotal for ensuring food security, as elucidated in the research by Mohamed *et al.* (2021). Such strategies enable growers to accurately administer the right amount of water based on plant needs and soil moisture levels, ultimately leading to increased irrigation efficiency and agricultural output. Conversely, inadequate irrigation management can result in water stress, infections, and fertilizer leaching, posing significant threats to crop health and productivity.

For plant physiologists and horticulturalists, reliable water stress indicators are indispensable for maximizing irrigation efficiency for future projects. These indicators enable researchers to determine the precise timing and volume of required irrigation, promoting sustainable and efficient irrigation practices.

The current review examines the most crucial water stress indicators in widely cultivated fruit trees, such as olive, citrus, and apple. Despite numerous research studies on these fruit trees, the results have often been inconclusive, primarily due to the long-term impact of climate change, which complicates data compilation. This review aims to stimulate further research in this essential area, particularly in light of the looming threat of climate change, which poses unprecedented challenges to fruit tree cultivation.

### *Morphological water stress ındicators*

Even though the roots are the first organ in plants to respond to drought conditions, due to the difficulty of observing root response in soil, many researchers have focused on the trunk response to drought rather than the root response. According to Ortuno *et al.* (2010), daily oscillations in trunk diameter, including regular swelling and shrinking patterns, are promising for scheduling irrigation in various fruit trees. In their respective papers, Corell *et al.* (2019) and Li *et al.* (2020) emphasized the importance of considering trunk growth rate as a valuable parameter among various options for assessing stress and planning irrigation.

Most plant species experience leaf architecture and ultrastructure changes due to water stress. Many morphological changes occur concurrently, including decreased leaf dimensions, decreased stomatal density, reinforcement of leaf cell walls, cuticle formation on the leaf surface, impeded development of the conductive system, and premature senescence. Despite potential losses in root dry weight and length within specific plant species, water stress increases the root/shoot ratio, improving water absorption and osmotic equilibrium.

**Olive:** Olive trees can undergo structural changes as a drought-resistance defence mechanism. Understanding these anatomical adaptations is critical for thoroughly understanding how plants resist stress. Regarding environmental conditions, the leaf is the most adaptable organ, and the effect of water stress is more strongly represented in leaf structures than in stems and roots (Ennajeh *et al.*, 2010). Tangu (2014) demonstrated that in response to insufficient water supply, the olive tree's leaf area decreases, the attachment angle of leaves to the branch contracts, and the leaves curl.

The variety determines the response of olive leaf anatomy to water stress. Ennajeh *et al.* (2010) discovered in their study that drought-resistant olive cultivars had significant changes in leaf shape, such as trichome density and stomatal density. As a result, they may be helpful in selecting drought-tolerant olive varieties.

Specific leaf anatomical parameters changed significantly under drought stress conditions. These changes were more pronounced in the *Zalmati* cultivar, which had a lower specific leaf area and higher foliar tissue density. When the performance of *Zalmati* olive trees was evaluated, it was discovered that this cultivar has greater drought tolerance than the *Chemlali* cultivar. This conclusion is supported by Boughalleb and Hajlaoui (2011), who observed a lower decline in relative growth rate, net assimilation rate, and chlorophyll fluorescence parameters, as well as thicker palisade parenchyma and higher stomatal and trichome density.

The average trunk growth rate is not the only factor to consider when scheduling olive tree irrigation, according to Corell *et al.* (2019). Instead, because they are strongly related to levels of water stress, the frequency and absolute value of daily trunk growth rate are regarded as more promising indicators of appropriate irrigation scheduling.

In their investigation, Fernández *et al.* (2011) discovered that maximum daily shrinkage is inefficient in forecasting water stress in trees. On the other hand, maximum trunk diameter proved to be an accurate predictor of the onset and severity of water stress in mature *Arbequina* olive trees carrying a heavy fruit load. Water status indicators, such as trunk diameter changes, can be used for irrigation scheduling, providing precise control over water distribution. However, as Giron *et al.* (2015) pointed out, few studies use these indications as the sole scheduling parameter, especially for olive trees.

**Citrus:** According to Alves Junior *et al.* (2012), water stress affected the root distribution of the *'Valencia'* orange tree, stimulating horizontal root growth. According to Zaher-Ara *et al.* (2016), stress conditions significantly decreased various stem and root-related growth metrics of citrus trees. However, El Bey *et al.* (2022) discovered that the partial root drying irrigation strategy did not affect the morphological features of orange trees, except for leaf dry weight.

Monitoring trunk diameter changes in *Navelina* oranges, according to Garcia-Tejero *et al.* (2011), is a valuable tool for determining water stress. Furthermore, they discovered that maximum daily shrinkage was highly sensitive to water stress compared to stem water potential and stomatal conductance.

**Apple:** Locatelli *et al.* (2019) carried out morphological experiments, focusing on leaves due to their well-known ability to adapt quickly. These studies discovered genetic variability among the apple cultivars, primarily influenced by anatomical differences indicating their potential for survival in water-stressed environments.

In their study, Doltra *et al.* (2007) discovered a strong relationship between maximum daily shrinkage and parameters such as reference evapotranspiration and noon stem potential. As a result of this discovery, maximum daily shrinkage has emerged as an intriguing and potentially useful tool for effective irrigation management. They also emphasized the importance of further research to develop reference values for maximum daily shrinkage and plant water potential indicators that account for evaporative conditions and different growth stages.

Maximum daily shrinkage must be established as a reference or baseline value. According to De Swaef *et al.* (2009), these values are frequently calculated by evaluating how plant water status changes throughout the seasons in settings with abundant soil water.

### *Physiological Water Stress Indicators*

Among commonly used physiological markers, leaf water potential stands out because it provides an overview of the plant's water state. According to Reddy (2019), maintaining a high leaf water potential is linked to systems that help the plant avoid dehydration. Both leaf water potential measured in the early morning and stem water potential have been identified as simple and reliable indicators of the plant's water status. However, Santesteban *et al.* (2019) pointed out that the timing and techniques for measuring water potential can vary and should be carefully evaluated to provide valuable data.

Stomata are critical regulatory systems in leaves, assisting in managing the tradeoff between water loss and photosynthesis. According to Lavoie Lamoureux *et al.* (2017), these tiny structures change their behaviour based on environmental inputs.

Stomatal conductance is an indirect measure of plant water stress because it represents the extent to which stomata are open, influencing leaf potential. Stomatal conductance is a time-consuming and labour-intensive method unsuitable for automation or industrial applications. Furthermore, when soil moisture is scarce, its precision decreases in anisohydric crops, which have less accurate control over leaf water status. Furthermore, as mentioned in a study conducted by Ihuoma and Madramootoo (2017), the significant variability in stomatal conductance among leaves within a plant canopy necessitates many repetitions to generate valid data for irrigation scheduling.

Stomatal closures are primarily regulated by ABA and are related to soil moisture content rather than leaf water state. Changes influence plant stomatal control in plant hydraulic conductance, nutritional condition, stem pH, and decreasing water content. Although stomatal closure reduces $CO_2$ absorption and net photosynthesis, it is an acceptable tradeoff for plant survival and growth to maintain a low transpiration rate and minimize leaf water loss.

The sap flow is a heat pulse-based measurement of transpiration. Calibration and complex instrumentation and expertise are required for each tree (Ihuoma and Madramootoo, 2017). Sap-flow sensors are devices that monitor the movement of sap as it ascends through xylem tissue. Sap flow is measured using two distinct techniques (Gimenez *et al.*, 2013). Gonzalez-Dugo *et al.* (2014) discovered that temperature-based indicators strongly link water status in various fruit tree species.

**Olive:** Moriana *et al.* (2012) enhanced existing water potential threshold values and irrigation methods, focusing on estimating olive tree irrigation requirements with an emphasis on midday stem water potential. Various studies (Naor *et al.*, 2013; Marra *et al.*, 2016; Ahumada-Orellana *et al.*, 2018) suggest that stem potentials ranging from -2.5 to -3.5 MPa are adequate to ensure satisfactory olive oil yield and quality, particularly for the Arbequina cultivar. However, Moriana *et al.* (2012) propose that severe stress is indicated by stem values as low as -4.0 MPa.

Examining the impact of drought stress on olive plants, Marino *et al.* (2018) categorized stem water potential into three groups: no stress (values below -2 MPa), moderate stress (values between -2.0 and -3.5 MPa), and high stress (values less than -3.5 MPa). According to their research, maintaining the water potential of olive stems between -2 and -3.5 MPa is optimal for efficient irrigation operations and helps prevent harmful stress.

Ahumada-Orellana *et al.* (2019) classified water stress as minor or non-existent when stomatal conductance exceeded 0.18 $mol/m^2/s$. Water stress was classified as moderate to severe when stomatal conductance fell significantly below this threshold.

Sensor placement, soil moisture levels, and climatic conditions can all impact sap flux measurements. Notably, Masmoudi *et al.* (2011) found a strong correlation between sap flux data and measurements of global radiation and reference evapotranspiration.

Fernandez *et al.* (2008) presented an automated irrigation control system for fruit tree orchards. This technique compares measurements collected from plants that have received excessive irrigation to sap flow data collected from the trunks of olive trees treated to irrigation to satisfy crop water requirements. In a separate study, Fernandez *et al.* (2011) demonstrated the utility of sap flow measurements in detecting water stress in olive trees. They also mentioned the method's ability to provide precise watering. However, several limitations stem from the approach's basic principles and the plant's physiological responses to water-related problems. Nonetheless, the method was thought to be reasonably practical in terms of detecting water stress early, reliably, and robustly.

The canopy temperature of olive trees was consistently lower than the air temperature in the control group but higher in stressed trees, with a maximum temperature differential of 2.7°C.

The most significant differences in canopy temperature and leaf water potential were observed between the two groups around midday. Because of the increased water deficit, canopy temperatures rose above the ambient air temperature, potentially affecting leaf function and crop output. According to Akkuzu *et al.* (2010), temperature gradients also influenced olive trees' water potential.

Canopy temperature is influenced by interactions between the soil, biosphere, atmosphere, and the plant's water status. Up to a point, increasing leaf temperature increases photosynthetic activity. Under soil water stress conditions, stomatal closure raises leaf temperatures above the optimum (Ben-Gal *et al.*, 2009).

**Citrus:** Ballester *et al.* (2011) and Sdoodee and Somjun (2008) highlight that assessing plant water status and planning irrigation in citrus plants commonly relies on stem water potential. However, this method faces limitations due to the temporal variability of stem water potential, preventing automation and restricting its application to a small number of trees.

Contrastingly, Sade *et al.* (2012) suggested that with their more adaptable leaves, citrus plants could sustain open stomata and high photosynthetic rates for extended periods, even in the face of declining leaf water potential. Aounallah *et al.* (2023) argue that leaf water potential emerges as a more dependable indicator of a plant's water status.

In their study, Aounallah *et al.* (2023) employed the partial root-drying irrigation method and observed a reduction in the leaf water potential of clementine trees. Specifically, during the initial season of fruit growth, there was a 35.9% decrease in stage II and a 13.5% decrease in stage III. In the subsequent season, these reductions persisted, with a 35.8% decrease in stage II and a 12.3% decrease in stage III. This research underscores the efficacy of leaf water potential as a reliable measure and the impact of irrigation methods on citrus plant water status.

In investigating water stress indicators, Garcia-Tejero *et al.* (2010) established that combined measurements of stem water potential and stomatal conductance exhibited robust and meaningful associations with citrus tree yield and fruit quality parameters.

Insufficient water in citrus plants reduces $CO_2$ absorption, conductance, and transpiration. In such conditions, the primary plant response involves stomatal closure, decreasing transpiration and hindering gas exchange, particularly $CO_2$ absorption. Studies by Pérez -érez *et al.* (2008), Rodriguez-Gamir *et al.* (2010), and Hutton and Loveys (2011) indicate that a decrease in photosynthetic rate results in reduced biomass production and growth. In irrigated orange trees, a decline in stomatal conductance was observed after twenty days, while Barreto *et al.* (2017) noted a significant decrease in stomatal conductance within just nine days for non-irrigated plants.

In a separate study, Ballester *et al.* (2013) employed the compensatory heat-pulse method to measure sap flow and quantify transpiration in Clementina de Nules and Navel Lane Late varieties. They found that sap flow sensors could be useful for detecting plant water scarcity, although they acknowledged challenges in precise transpiration measurement.

The use of thermal imaging as a water stress indicator was explored, revealing that canopy temperature serves as a more sensitive predictor of water status in persimmon trees compared to citrus trees. The heightened sensitivity of persimmon trees is attributed to their larger leaf size, which increases canopy resistance and results in more noticeable temperature elevation due to water stress, primarily through stomatal closure (Ballester *et al.*, 2013).

Garcia-Tejero *et al.* (2011) observed that changes in canopy air temperature differentials in Navelina oranges effectively detect water stress as particularly sensitive indicators. Romero-Trigueros *et al.* (2019) also found that the crop water stress index calculated using infrared thermometry exhibited the strongest relationship with stem water potential. This underscores the utility of infrared thermometry in assessing the water condition of water-stressed grapefruit plants. Gonzalez-Dugo *et al.* (2014) emphasized the need to consider new growth at the top of the canopy, short-term fluctuations in canopy temperature, and the use of high-resolution airborne thermal imagery when using the crop water stress index in both navel orange and mandarin trees.

**Apple:** Water-stressed plants were categorized as mild when the difference in water potential between stressed and well-watered (control) plants ranged from 0.1 to 0.5 MPa, moderate when the difference fell between 0.5 and 1.5 MPa, and severe when the difference exceeded 1.5 MPa.

In instances of severe drought stress, stomatal conductance exhibited an 88.26% reduction for Red Chief grafted onto MM106 and an 82.9% reduction for Red Chief grafted onto M9. Mahouachi (2009) suggests that the decrease in stomatal conductance acts as a defensive mechanism to reduce water loss from the leaf surface. Contrary to reactions observed in moderate drought cases, Aras and Keles (2019) highlighted that the impact of drought stress on apple plants varied based on factors such as the rootstock used, drought severity, and duration. Extreme drought conditions were found to be detrimental to apple tree viability, reducing stomatal conductance in both studied cultivars and resulting in decreased transpiration (Sircelj *et al.*, 2007).

The sap flow index in apple trees emerges as a highly responsive indicator of sap flow rate, capable of detecting even minor re-saturating flows during the night and early morning hours. During drought conditions, the Hongro apple cultivar experienced a greater reduction in stem sap flow compared to the Fuji apple cultivar, attributed to notable reductions in xylem vessel area, density, and diameter. Stem sap flow reduction under drought stress coincided with increased Abscisic acid levels (Bhusal *et al.*, 2019).

Liu *et al.* (2012) investigated sap flow differences during two critical periods of apple tree growth. The early period of rapid leaf expansion was primarily influenced by vapor pressure deficit, evapotranspiration, and leaf area index, while the second stage of fruit enlargement saw primary influences from vapor pressure deficit, evapotranspiration, and soil water content. Sap flow demonstrated a strong inverse linear relationship with leaf water potential and a positive relationship with maximum daily stem shrinkage.

The crop water stress index measured at solar noon emerged as a reliable indicator of water status in fruit plants. Mohamed *et al.* (2021) compared the crop water stress index estimated for apple trees during morning and solar midday hours in response to variations in soil water deficit and soil water potential. The findings indicate that the morning crop water stress index accurately predicts plant water stress in apple trees, allowing for timely watering to maintain tree hydration.

***Fruit quality parameters as indicators of water stress***

**Olive:** The scientific literature highlights varied responses to water stress that impact the quality of both olive fruit and olive oil. The management of water resources significantly influences the characteristics of the fruit. An important parameter for assessing the impact of water stress is the oil content of olive fruit. Conde-Innamorato *et al.* (2022) observed that the effect of water restriction on oil content differs among olive cultivars, revealing no impact on the oil content of Arbequina olives but an increase in Frantoio olives.

Similarly, Arbizu-Milagro *et al.* (2022) found that under water scarcity, fruit oil content increased, influenced by factors such as olive cultivar, agricultural practices, and local climate conditions. Additionally, irrigation has shown positive effects on various fruit characteristics, including increased fresh weight, volume, mesocarp-to-endocarp ratio, chlorophyll content, and mesocarp water content (Conde-Innamorato *et al.*, 2022). However, it tends to reduce fruit firmness and sugar content, parameters useful for assessing the impact of water stress on fruits.

Water management practices can also impact olive oil quality criteria. Indicators such as olive oil acidity and peroxide value are useful for evaluating the effectiveness of irrigation regimes (Ghrab *et al.*, 2014). Furthermore, chemical compounds in olive oil, such as phenolic compounds and fatty acids, are identified and quantified as valuable water stress indicators. The amount of water applied to olive trees notably influences these compounds and is a primary focus when studying the effects of irrigation practices on olive oil quality.

Research on the effect of irrigation on olive oil composition has produced conflicting results. While studies by Conde-Innamorato *et al.* (2022) and Arbizu-Milagro *et al.* (2022) indicate different effects on triglyceride accumulation, others, like Ghrab *et al.* (2014) and Caruso *et al.* (2014), report no impact on olive oil composition.

Some studies, such as those conducted by Caruso *et al.* (2014), suggest that polyphenol content may decrease in water deficit conditions. Conversely, experimental studies by Andria *et al.* (2008) and Ghrab *et al.* (2014) demonstrate that phenol levels can decrease with increasing applied water. Specific phenolic compound levels, as highlighted by Machado *et al.* (2013), can serve as indicators of a plant's water status, with concentrations decreasing as the applied water amount increases during irrigation. Moreover, Jimenez-Herrera *et al.* (2019) discovered significant changes in the concentration and content of oleuropein, tyrosol, and hydroxytyrosol in response to drought-induced water stress.

The reaction concerning fruit quality and, consequently, olive oil quality is intricate, influenced by cultivar, growth season, and environmental conditions. Thus, advocating for adequate water availability during fruit development is crucial for optimal growth and quality, emphasizing the need for further research in this field.

**Citrus:** Prior studies have demonstrated that water stress exerts an impact on fruit output during blooming and the initial stages of fruit development (Pérez-Pérez *et al.*, 2008; Garcia-Tejero *et al.*, 2010; Pérez-Pérez *et al.*, 2014). This stress tends to reduce fruit size, yield, and delay maturation, while simultaneously enhancing several quality metrics during the fruit growth phase (Navarro *et al.*, 2010; Ballester *et al.*, 2013; Pérez-Pérez *et al.*, 2014; Navarro *et al.*, 2015). Notably, the application of a water deficit at the onset of the ripening stage has been associated with increased sugar content, citrus acidity, and palatability of citrus *flavour* (Obenland *et al.*, 2008). During maturation, deficit irrigation positively influences total soluble solids and titratable acidity in citrus fruit without significantly delaying maturation time or affecting fruit yield (Pérez-Pérez *et al.*, 2009; Garcia-Tejero *et al.*, 2010; Navarro *et al.*, 2010; Navarro *et al.*, 2015). Da Silveira *et al.* (2021) affirm that soil water availability plays a crucial role in determining various fruit quality attributes.

Numerous studies in the past have demonstrated that deficit irrigation practices lead to specific outcomes, including reduced acidity, improved maturity index (Silveira *et al.*, 2020), and increased firmness and total soluble solids in citrus fruits (Zhou *et al.*, 2017; Zhong *et al.*, 2019). El Bey *et al.* (2022) made the intriguing discovery that implementing deficit irrigation techniques during the second and third stages of fruit growth moderately reduced fruit size, weight, volume, and fruit juice quantity. Surprisingly, this approach enhanced the thickness and color index of orange fruits. Moreover, water restriction significantly increased total soluble solids and pH levels, possibly linked to an osmotic adjustment mechanism involving organic solute accumulation.

Employing the deficit irrigation technique to fulfil only 50% of the water requirements for Clementine trees during fruit growth phases II and III demonstrated no adverse effects on fruit quality. Consequently, this efficient irrigation approach holds promise in addressing water scarcity challenges in semi-arid and arid climate regions (Aounallah *et al.*, 2023).

**Apple:** There has been little research into the effects of irrigation restrictions on the nutritional status and physical and chemical properties of various horticultural trees, including apple trees. Mihaljevie *et al.* (2021) discovered that apple trees have developed antioxidant defense mechanisms, and these antioxidants, when quantified in the fruits, can serve as indicators of water stress.

According to Abdel-Sattar and Ktob (2021), various factors such as fruit yield, yield increment, fruit firmness, total soluble solids, total and reducing sugars, and anthocyanin content can be used to evaluate the effectiveness of an irrigation system. Furthermore, some authors have shown that a lack of water promotes the accumulation of terpenes in apple fruit (Bianco *et al.*, 2008).

Xu and Ediger (2021) investigated different stress indicators related to fruit quality. Their research aimed to delve into water utilization strategies and the potential mechanisms underlying drought susceptibility and resistance. Nonetheless, due to the influence of water stress on numerous molecular and biochemical processes in fruits, the impact of water stress on fruit quality and postharvest changes remains complex and variable.

Water stress primarily impacts olive tree leaves, resulting in reduced leaf area, connection angle, and curling, while increasing stomatal and trichome density. Trunk growth rate serves as an early indicator of water stress. Precise irrigation is facilitated by sap flow measurements, with water availability during fruit development crucial for optimal growth. In citrus trees, reliable indicators include maximum daily shrinkage and stem water potential, while the crop water stress index, utilizing infrared thermometry, accurately predicts water stress. Citrus fruit quality is influenced by water deficit severity and growth stage. For apple trees, maximum daily shrinkage proves promising as an irrigation control tool. Midday stem water potential serves as a superior predictor of water stress for fruit size compared to leaf water potential. Drought stress reduces stomatal conductance, influenced by severity, duration, and rootstock. The sap flow index is sensitive and correlates with leaf water potential, reliably assessing fruit tree water status. Antioxidant defense mechanisms in apples signal water stress and irrigation management, which are predictive of fruiting success, yield, and quality. Water deficiency increases terpenes, while drought stress markers include zeaxanthin and glutathione. Water stress affects phenol and peroxidase in apple rootstocks, but its impact on fruit quality is intricate and unpredictable.

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