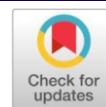


Review Article

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Canopy infrared thermography for water stress assessment in fruit crops

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ABSTRACT

Efficient irrigation management is vital for optimizing water use in fruit crops, enhancing both yield and quality while conserving valuable water resources. Infrared thermography (IRT) has become a valuable non-invasive method for assessing plant water status providing real-time insights that facilitate more accurate irrigation decisions. This comprehensive review examines the role of IRT in managing irrigation for fruit crops. By capturing thermal images of crop canopies, IRT allows for the visualization of temperature variations linked to water deficiency, facilitating timely and accurate irrigation adjustments. Despite its potential, practical implementation of IRT faces challenges such as environmental variability, canopy heterogeneity, and the need for calibration across crops and conditions. Various thermal indices including Stress Degree Days (SDD), Crop Water Stress Index (CWSI), Degrees Above Canopy Threshold (DACT), Time Temperature Threshold (TTT) and Temperature Stress Day (TSD), are employed to evaluate plant water stress under field conditions. The consistent monitoring and interpretation of these indices during critical growth stages supports informed decision-making for irrigation management. This review contributes to the understanding of how IRT-based thermal indices can enhance precision irrigation and improve water use efficiency in fruit crops.

Keywords: Infrared thermography, Plant water stress, Canopy temperature, Crop water Stress indices, Schedule irrigation, Plant water status, Thermal Images

1. INTRODUCTION

Fruit crops play a crucial role in addressing global hunger, and poverty by providing essential nutrients and income opportunities. Fruits that are rich in vitamins and antioxidants contribute significantly to improved nutrition, especially in regions where malnutrition is prevalent [52]. For smallholder farmers, fruit cultivation offers economic stability by diversifying income sources and lifting them out of poverty, particularly in developing countries. To meet future fruit production demands, understanding the intricate relationship between agricultural productivity and water usage is crucial, especially given mounting concerns about water scarcity and climate change impacts.

As global demand for fruits rises due to population growth, urbanization, and dietary shifts, the pressure on water resources for irrigation intensifies. Fruit crops, like other agricultural commodities, require substantial amounts of water for optimal growth and yield. The water requirements of fruit crops differ based on factors like the type of fruit, stage of growth, climate, soil properties, and agricultural practices. With global temperatures projected to rise in the coming decades, an increase in evaporation rates and the expansion of arid regions are anticipated. This trend is expected to lead to a higher demand for irrigation water, exacerbating existing water scarcity issues worldwide [17]. As a result, limited water availability is expected to become a major constraint on future plant growth, highlighting the increasing need for irrigation

methods that improve water efficiency in agriculture. It is essential to consistently track soil moisture levels and adapt irrigation schedules according to the crop's specific needs to optimize water utilization efficiency. Both over-irrigation and under-irrigation can negatively impact fruit quality, crop yield, and the overall health of the plants. Therefore, it is essential to understand the unique water requirements of various fruit crops and adapt irrigation strategies to optimize yield and improve fruit quality. Regulated deficit irrigation (RDI) has been used successfully in various fruit crops [51] and the effectiveness of this approach depends on the severity of water stress experienced by the plants. Hence, detection of plant water stress is crucial.

Various plant parameters, such as stem water potential and stomatal conductance, are utilized to estimate water status of the plants about soil moisture levels. These methods are time-intensive, laborious, and unsuitable for mechanization [41, 60, 61]. Conventional sensing technologies like soil moisture sensors, neutron moisture meters, and tensiometers measure soil moisture in the field, not crop water requirements. Among various crop sensing technologies, infrared thermography (IRT) is most suitable for detecting the water status of fruit crops due to its non-destructive nature. Infrared thermography detects infrared radiation from a body and represents it as a spatial mapping of the surface temperature.

The significance of canopy temperature as an indicator of crop water stress became apparent in the 1960s [21]. Water deficits can lead to stomatal closure, reducing transpiration and raising leaf temperature [8, 34]. Thermal imaging cameras can measure the increase in temperature of the canopy and leaves [70]. The canopy temperature (T_c), derived from infrared images, is widely used in agriculture to assess water stress in plants, aiding in efficient irrigation scheduling [36, 56, 63, 54].

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In this comprehensive review, we explore the importance of infrared thermography for efficient irrigation management in fruit crops, examining its potential to replace traditional methods and improve water use efficiency in agriculture.

2. Basic Principle of Infrared Thermography

Infrared thermography (IRT) is based on the concept that every object releases infrared radiation, which is directly related to its temperature. The intensity of the radiations increases with temperature. Infrared cameras capture this radiation and convert it into electronic signals, which are then processed to produce thermal images or thermograms (Fig. 1). These images provide visual and quantitative data on the temperature distribution across the plant canopy. This method allows non-contact temperature measurements and the identification of thermal anomalies or patterns. Infrared refers to a portion of the electromagnetic spectrum that is invisible to the human eye, with wavelengths between 0.75 and 100 nm. A material's emissivity and temperature both influence its radiation emission. According to O'Donnell *et al.* (2014), a thermal image can be either coloured or monochromatic, with a color shift expressing material thermal fluctuations.

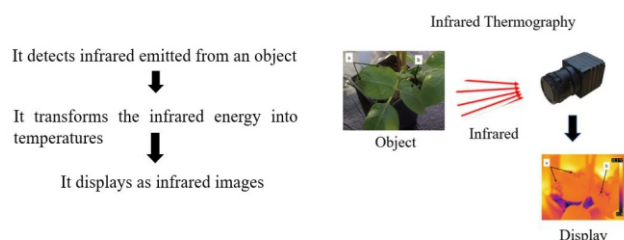


Figure 1: Principle of Infrared thermography

3. Water Stress Detection and Irrigation Scheduling: One of the key uses of infrared thermography (IRT) in fruit crops is the early detection of water stress. When plants experience water stress, their leaf temperatures rise due to decreased transpiration. IRT can detect these temperature changes, allowing for timely irrigation to avoid yield loss and deterioration in quality. [3] demonstrated that thermography was effective in identifying water stress in citrus and persimmon trees exposed to varying levels of deficit irrigation. The study revealed significant temperature differences, with a maximum of 4.4°C in persimmon trees and 1.7°C in citrus trees when comparing deficit-irrigated trees to controls. The effect of water stress on the canopy temperature varies between citrus and persimmon trees, partly due to the larger leaf size of persimmons compared to citrus.

Similarly, in olive trees, which have leaf sizes comparable to citrus trees, [53] observed a canopy temperature difference of 2°C between irrigated and non-irrigated trees. [61] found that grapefruit and citrus plants under reduced irrigation exhibited canopy temperatures up to 6°C higher than the surrounding air, making it straightforward to identify water-stressed plants using thermal imaging. In a study by [62], they recorded differences in canopy-to-air temperatures at midday in plants experiencing water stress, with values ranging from 5-7°C, while non-water-stressed peach plants showed lower values around 1.4-2°C. Additionally, [33] reported that in various irrigation treatments, moderate and severe water-stressed sesame plants had higher canopy temperatures by 1.9°C and 2.6°C, respectively, compared to well-watered plants under greenhouse conditions. These studies highlight the effectiveness of thermography in detecting and understanding plant water stress across different irrigation conditions,

suggesting its utility for managing irrigation schedules in orchards with considerable variations in water stress. [20] connected canopy temperature and trunk diameter changes with other physiological indicators for managing water stress in citrus orchards. They found that maximum daily shrinkage and the canopy-to-air temperature difference were more sensitive to water stress than stem water potential and stomatal conductance. This sensitivity is linked to reduced phloem reservoirs during deficit irrigation periods [55, 19] a finding consistent with observations in lemon (*Citrus limon* (L.)) [44] and grapevine (*Vitis vinifera* L.) [28].

Effective irrigation scheduling is crucial for maximizing water efficiency and ensuring crop health. Canopy temperature-based crop water stress indices (CWSIs) have proven to be valuable tools for evaluating crop water status and making informed irrigation decisions. In addition to canopy temperature, crop water stress is analyzed using various indices, which reflect differences in stomatal opening and evaporation rates as plant water content decreases. Each of these indices provides unique insights into the physiological status of the crop, which may include measurements such as leaf relative water content and stomatal conductance, aiding in the development of informed irrigation management strategies.

4. Canopy temperature-based Water Stress Indices

Since the introduction of portable infrared thermometers in the 1960s, researchers have extensively utilized thermal indices, especially canopy temperature, to monitor crop water stress and optimize irrigation scheduling over the past fifty years. Several thermal indices, including Stress Degree Days (SDD), Crop Water Stress Index (CWSI), Degrees Above Canopy Threshold (DACT), Time Temperature Threshold (TTT), and Temperature Stress Day (TSD) [26] (Fig. 2), have been utilized to assess plant water stress in field conditions. Regular monitoring and analysis of these indices during key growth phases allow for informed irrigation decisions. By adjusting irrigation practices according to these indices, water usage can be optimized, and stress-related effects on crop yield and quality can be mitigated.

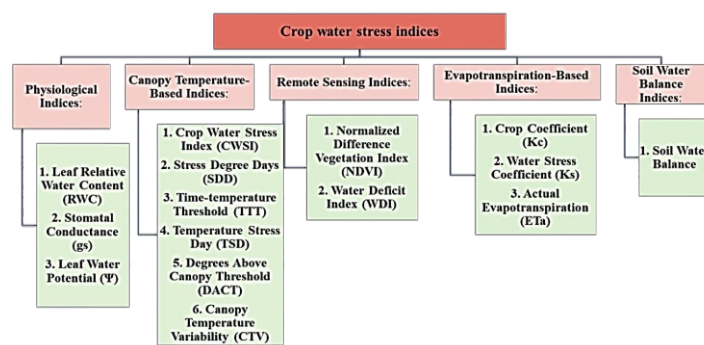


Figure 2: Classification of crop water stress indices

Stress degree days (SDD): Air temperature plays a crucial role in normalizing environmental factors for monitoring crop water stress using canopy temperature-based approaches. Early research by [14] explored the link between the difference in temperature between leaves and air and plant water stress. Building on this, [27] and [31] suggested that the difference between canopy temperature and air temperature ($T_c - T_a$) can be indicative of water stress. When plants experience water stress, partial stomatal closure reduces transpiration, causing sunlit leaves to heat up more than the surrounding air due to increased absorption of solar energy. To quantify crop water stress, they introduced the Stress Degree Day (SDD) concept,

which measures the cumulative difference between canopy and air temperature over time throughout the crop's growth cycle. This thermal index, one of the earliest and most widely adopted, provides a quantitative method for assessing water stress in crops through SDD.

$$SDD = SDD = \sum_{n=1}^N (T_c - T_a)$$

where n is the period of study and (T_c - T_a) is the canopy-air temperature difference. In studies using canopy temperature to assess water stress, other researchers have built upon these early concepts. [20] observed that Sweet Orange plants subjected to sustained deficit irrigation (SDI) exhibited greater differences between canopy and air temperatures (T_c - T_a) compared to those receiving full irrigation (C-100). They confirmed that variations in this temperature differential are effective for assessing water stress. Similarly, [4] used canopy temperature (T_c) to predict the impact of deficit irrigation on citrus fruit weight. They found that a 1°C increase in (T_c - T_a) during water restriction periods was associated with a reduction of 5.3 grams in fruit weight, demonstrating that thermographic measurements of canopy temperature can be useful for predicting the effects of water deficits on citrus fruit weight. Earlier in wheat, [7] established a linear relationship between cumulative SDD and grain yield in wheat. They observed that higher cumulative SDD values before irrigation were linked to increased grain yield, and irrigation was scheduled when the cumulative SDD value reached -143.4.

Critical Water Stress Index (CWSI): Canopy temperature-based variables, such as Stress Degree Days (SDD) and Temperature Stress Days (TSD), aim to relate canopy temperature to air temperature. However, since

evapotranspiration demand, which greatly affects crop water stress, is influenced by the vapor pressure deficit (VPD) of the air, the Crop Water Stress Index (CWSI) offers a more refined approach. The CWSI normalizes the difference between canopy temperature and air temperature (CATD) with VPD to quantify crop water stress [25, 26, 30, 58]. The CWSI calculation requires two key baselines: the non-water-stressed baseline, which corresponds to a well-watered crop, and the maximum stressed baseline, which represents a crop with fully closed stomata and minimal transpiration. The index is computed using the formula:

$$CWSI = (T_c - T_a) - D2 / D1 - D2$$

where D1 is the maximum canopy-air temperature difference for a fully stressed crop, D2 is the lower limit of canopy and air temperature difference for a well-watered crop, T_c is the measured canopy surface temperature, and T_a is the air temperature. The CWSI has been shown to correlate well with plant water status [29, 64]. This index provides a quantitative framework for interpreting thermal data from crop canopies, aiding in irrigation and management decisions (Table. 1). Recent studies illustrate the utility of CWSI in different crops. [2] used thermal cameras to assess the CWSI in Mandarin plants, finding higher values in plants under deficit irrigation and lower values in those with full irrigation, reflecting the impact of water availability on crop water stress. In vineyards, [6] reported that well-watered grapevines had lower CWSI values (below 0.5), while the most stressed vines had values around 1.0. Similarly, [57] also found that well-irrigated pistachio plants had CWSI values rarely exceeding 0.2, whereas plants under Regulated Deficit Irrigation (RDI) showed values between 0.8 and 0.9.

Table 1: Crop water stress index values to schedule irrigation in various fruit crops

Crop	CWSI Values	Observations	Study
Mandarin	Higher values under deficit irrigation; Minimum values under complete irrigation	Higher CWSI indicates greater water stress	[2]
Vineyards	Well-watered: < 0.5; Stressed: ~1.0	Lower CWSI in well-watered grapevines	[6]
Pistachio Nut	Well-irrigated: rarely exceeds 0.2; RDI: 0.8-0.9	Higher CWSI under Regulated Deficit Irrigation (RDI)	[57]
Apricots, Peaches, Almonds	Apricots: 0.27; Peaches: 0.37; Almonds: 0.31	CWSI thresholds for irrigation	[24])
Indian Mustard	Mean CWSI: 0.4	Optimal yield and maximum water use efficiency at 0.4 CWSI	[35]
Apple Trees	More responsive CWSI measured at late morning hours	CWSI helps detect water stress earlier in the day	
Eggplant	0.18-0.20	Optimal CWSI values for high and good-quality yields	(Çolak et al., 2015)
Grapevine	0.20	Optimal CWSI values for high and good-quality yields	(Colak and Yazar, 2017)

Scheduling irrigation based on stress indices is a holistic approach that considers the specific water needs of fruit crops during critical periods [43]. [24] identified specific Crop Water Stress Index (CWSI) thresholds for initiating irrigation. According to their findings, the recommended CWSI thresholds are 0.27 for apricots, 0.37 for peaches, and 0.31 for almonds. Similarly, in pecan nuts, optimal yield, nut size, and tree growth were achieved with irrigation scheduled at a Crop Water Stress Index (CWSI) of 0.08 or lower. Conversely, irrigating at a CWSI of 0.20 led to reduced yields, smaller nut weights, decreased tree growth, and lower yield efficiencies. [35] found that for Indian mustard (*Brassica juncea*), an irrigation treatment corresponding to 30% soil moisture depletion (SMD) with a mean CWSI of 0.4 resulted in the best yield and highest water use efficiency. Additionally, [38] conducted a study on apple trees, revealing significant differences in canopy and air temperatures between stressed and non-stressed orchards.

They also compared CWSI measurements taken at midday with those taken in the late morning. The study found that late morning CWSI measurements were more sensitive to soil moisture changes, enabling earlier detection of water stress and improving irrigation scheduling.

Canopy temperature variability

Research on canopy temperature has demonstrated that crops experiencing water stress tend to exhibit greater variability in canopy temperature compared to those with adequate water supply [9, 42]. This variability in canopy temperature is influenced by environmental factors such as air temperature and radiation led researchers to investigate temperature variations in the field due to the uneven soil drying could serves as an indicator of plant water status. The concept of "canopy temperature variability" (CTV) was later introduced by Aston and Van in 1972 as a method for assessing crop water stress.

Canopy temperature variability refers to the differences in temperature across a plant's canopy. Using CTV to guide irrigation decisions offers potential for significant water savings by improving the efficiency of soil water use.

In a detailed study by [22], the effectiveness of the CTV approach under different moisture stress levels was examined. The study found that CTV remained relatively low under low moisture stress but became highly sensitive to water stress at moderate levels. They suggested that irrigation decisions should be considered when the CTV falls within the range of 0.5°C to 1.5°C. One challenge with the CTV approach is the variability in water availability in the root zone across fields, making it difficult to establish consistent threshold values or reliable connections with other stress indices.

Degrees above Canopy Threshold (DACT)

[13] introduced the concept of Degrees above Canopy Threshold (DACT), which measures the temperature difference above the critical temperature ($T_{critical}$) for a specific crop. The DACT is computed as:

$$DACT(h) = \text{Max}[0, T_c(h) - T_{critical}]$$

In this equation, T_c represents the crop canopy temperature at a given time (h), and $T_{critical}$ refers to the crop's threshold temperature. If the value of DACT is zero, it indicates no stress conditions, assuming that the crop canopy temperature is below $T_{critical}$. In a study by [40], they assessed canopy temperature-based water stress indices for soybeans grown under both irrigated and rainfed conditions in a subhumid environment. According to their findings, they discovered that more extensive Degrees above the Canopy Threshold (DACT) seasonal values were associated with decreased yields. A DACT value of approximately 2.3°C was identified as a threshold indicating well-watered conditions, implying that irrigation should be applied if this threshold is surpassed.

Temperature Stress Day (TSD)

The temperature variation between the canopy of stressed and non-stressed plants has also been used as an indicator for measuring moisture stress. To measure plant water status by deriving a relative measure from the temperature difference between a well-watered area and a stressed area, which are termed as "temperature stress day" (TSD). Additionally, [9] further proposed using TSD thresholds of 1.0 and 3.0 to determine irrigation timing for corn [*Zea mays* (L.)]. The simplicity of the TSD method comes from its reliance on only the simultaneous measurement of canopy temperatures in both stressed and well-watered fields with the same crop and soil conditions, without needing additional atmospheric or plant-related measurements. However, [10] cautioned that TSD is not completely independent of environmental factors, as it exhibits a strong dependency on air vapour pressure deficit, limiting its universal applicability.

Time-Temperature Threshold (TTT)

This method has been utilized to assess crop water stress and optimize irrigation scheduling. [59] were granted US patent 5,539,637 for an irrigation management technique known as "temperature-time threshold" (TTT) method. This approach recommends initiating irrigation when the canopy temperature exceeds a specific threshold for a designated time period. In cotton, [46] compared yields from automatic irrigation triggered by the TTT method with those from manually scheduled irrigation based on neutron probe readings.

They observed higher yields when irrigation was automated and triggered after canopy temperatures surpassed 28°C for over 452 minutes. [64] noted that a 4-hour TTT provided yields similar to 2 and 2.5-hour thresholds but used less water in cotton. The TTT method has also been applied successfully in crops such as soybean [16, 49] and corn [15, 16].

Variables based on canopy temperature, like CATD (or SDD), CTV, or TSD, aim to standardize canopy temperature with the surrounding air temperature. However, the evapotranspiration demand, which plays a key role in crop water stress, is largely influenced by the vapor pressure deficit (VPD) of the air. The Crop Water Stress Index (CWSI) is an important tool that adjusts CATD with VPD to measure crop water stress [25, 26, 30]. Though CWSI shows promise for quantifying crop water stress, there are several challenges to implementing it at the field scale. Despite the scientific robustness of CWSI, its application is limited by the complexity of measuring air temperature and humidity simultaneously. This process is often too complicated for farmers. Establishing a baseline for stressed and non-stressed crops is the most crucial aspect of the CWSI method. Moreover, the measurement of canopy temperature is typically conducted when the crop canopy fully covers the soil. Including background soil in temperature readings can result in incorrect assessments of water stress.

Water deficit index (WDI)

The Water Deficit Index (WDI) is calculated using the surface-to-air temperature difference combined with vegetation indices to estimate the relative water status of a field. The method is based on a trapezoidal model with four vertices representing distinct field conditions: a well-watered crop with full canopy cover, wet bare soil, a fully stressed crop with full canopy cover, and dry bare soil. By plotting canopy cover percentage against the surface-air temperature difference, the position of the target area is evaluated relative to the fully stressed and non-stressed extremes (Fig.3). This approach effectively corrects for temperature distortion caused by exposed soil, which may differ thermally from the plant canopy. The WDI is widely used in satellite-based crop stress monitoring, where vegetation cover is assessed using remote sensing indices such as NDVI, SAVI, or surface albedo, and canopy temperatures are derived through thermal imaging and land surface temperature measurements.

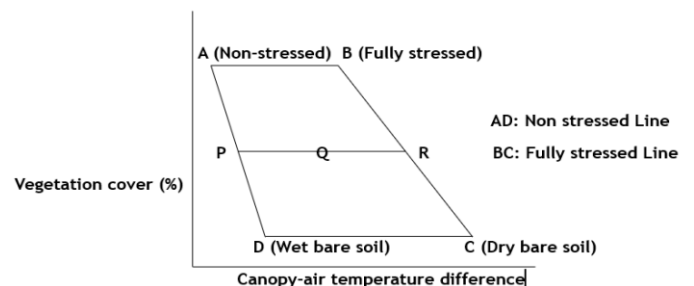


Figure 3: Canopy-Air Temperature Difference (CATD) Model for Calculating Water Deficit Index (WDI)

5. Canopy temperature variability and irrigation scheduling: Plant water status can be evaluated through measurements of leaf water potential or stomatal conductance. However, these measurements often show inconsistencies due to variations between leaves on the same plant and even greater differences across plants in a field. This variability makes it difficult to assess the overall water status of a crop accurately. Consequently, current practices involve sampling a limited number of leaves, which may not provide a comprehensive

assessment of the crop's water condition. Leaf temperature is often used as an indicator of stomatal conductance and water stress, with several studies by [26, 30, 32] supporting this approach.

Thermal imaging presents a promising alternative to direct leaf measurements by allowing water status assessment across larger areas, providing a more comprehensive view of crop hydration. It can effectively replace direct LWP measurements, as spatial mapping with thermal imaging can more accurately depict field-wide crop water status than traditional methods. Infrared thermography (IRT) enables the detection of spatial variability in water status within a field, making it a valuable tool in precision agriculture [50]. This data is crucial for implementing site-specific irrigation strategies, ensuring that each area receives the appropriate amount of water based on its needs. [11] explored the potential of using thermal images to estimate the water status of cotton under different irrigation regimes. Their study found that maps based on the Crop Water Stress Index (CWSI) were more effective in distinguishing between irrigation treatments than using leaf temperature alone. Additionally, incorporating spatial patterns into the classification process improved the accuracy in matching irrigation levels with actual field conditions.

For example, utilizing thermal infrared radiation (TIR) to evaluate spatial variations in soil water availability has demonstrated that plant growth and soil water deficits fluctuate both spatially and temporally within a crop field. An increased soil water deficit in the root zone leads to higher canopy temperatures, resulting in increased stomatal conductance. This relationship can be used to effectively schedule irrigation [47]. Additionally, [32] concluded that the infrared thermography approach is suitable for quantitative studies of spatial and temporal variations in conductance over a single leaf or for remotely screening large numbers of leaves of *Phaseolus vulgaris* L. for stomatal conductance.

7. Biochemical and Physiological Mechanisms Underlying IRT-Measured Plant Water Stress

The physiological response of fruit crops to water stress, as measured by infrared thermography (IRT), is directly correlated with underlying biochemical changes, including alterations in photosynthetic pigments (e.g., chlorophyll), stomatal conductance, and antioxidant enzyme activity (e.g., superoxide dismutase, catalase).

Photosynthetic Pigments: Water stress impacts the plant's chlorophyll content, the key pigment involved in photosynthesis. Chlorophyll degradation is a common response to stress, including drought, as it affects the photosynthetic apparatus in the chloroplasts. Reduced chlorophyll content decreases the efficiency of light absorption, thus lowering the rate of photosynthesis. Since photosynthesis is a primary process for cooling leaves (through water evaporation and transpiration), a decrease in its efficiency due to lower chlorophyll levels contributes to higher leaf surface temperatures. IRT effectively detects this temperature difference by capturing thermal radiation emitted from the leaves, thus providing a non-invasive way to monitor water stress.

Stomatal Conductance: Stomatal conductance, the rate at which carbon dioxide enters and water vapor exits through the stomata, is closely related to water status. Under water stress,

stomata close to prevent water loss, which leads to reduced transpiration. The reduction in transpiration raises leaf temperatures because evaporative cooling is diminished. By using IRT, leaf temperature can be monitored as an indicator of stomatal conductance. A Study in grapes has demonstrated that as stomatal closure progresses, leaf temperatures increase, making IRT a reliable tool for assessing water stress in real-time [32].

Antioxidant Enzyme Activity: Water stress induces oxidative stress, which results in the production of reactive oxygen species (ROS) such as superoxide radicals and hydrogen peroxide. Plants activate antioxidant defence mechanisms, including enzymes like superoxide dismutase (SOD), catalase (CAT), and peroxidase, to detoxify ROS and mitigate damage to cellular structures. The activity of these antioxidant enzymes increases during water stress as the plant attempts to maintain cellular integrity. Although IRT does not directly measure antioxidant enzyme activity, increased leaf temperatures detected by IRT can be associated with the internal biochemical stress responses, such as increased ROS scavenging and reduced transpiration.

8. Advantages of Using Canopy Temperature-Based CWSIs

Canopy temperature-based Crop Water Stress Indices (CWSIs) offer significant advantages for efficient irrigation management in fruit crops, along with some limitations (Table 2). They enable non-invasive, remote monitoring using infrared thermography, reducing plant stress and facilitating continuous assessment without damage. CWSIs support large-scale monitoring, making them ideal for extensive farming operations, and reduce the time and labor required for water stress assessment compared to traditional methods. Early detection of water stress allows for proactive irrigation adjustments, improving crop health and optimizing water use efficiency. CWSIs also support precision agriculture by providing detailed spatial information on water stress variability, enabling site-specific irrigation strategies that optimize water usage and improve crop productivity. Integration with modern technologies such as drones, satellites, and automated irrigation systems enhances data accuracy and ease of collection, allowing for real-time monitoring and irrigation adjustments. This leads to improved irrigation management decisions, reduced costs, and better crop yields. Efficient irrigation using CWSIs contributes to environmental sustainability by optimizing water usage, reducing waste, and minimizing runoff and leaching, which is crucial in water-scarce regions.

9. Integration of IRT with modern orchard management technologies

The application of infrared thermography (IRT) in irrigation management is greatly enhanced by integrating it with modern agricultural technologies. Drones fitted with thermal cameras can capture high-resolution thermal images across vast agricultural fields, offering detailed spatial information on crop water status. This integration facilitates real-time monitoring and automated irrigation adjustments based on current water stress levels. Additionally, satellite-based thermal imaging offers a broader perspective, enabling regional-scale water stress assessment and supporting large-scale irrigation management practices. The combined use of advanced UAVs with high-precision thermal cameras and infrared sensors has greatly enhanced the capability to monitor crop water status [5, 39].

Numerous studies have evaluated crop water stress conditions in various crops, such as those conducted by [65, 66, 67, 24]. However, the calibration and processing of thermal images can be time-consuming and empirical, limiting the practicality of high-precision thermal cameras for daily use on extensive arable land.

Table 2: Advantages and limitations of various CWSIs

Index	Advantages	Limitations
Crop Water Stress Index (CWSI)	- Provides a normalized measure of water stress - Useful for different crops and growth stages. - Helps monitor stress over time.	- Requires calibration for specific crops and conditions. - Can be complex to implement and interpret.
Stress Degree Days (SDD)	- Incorporates cumulative stress over time. - Can be used to predict impacts on crop yield.	- Requires accurate temperature data and calibration. - May not account for other stress factors (e.g., soil conditions).
Canopy Temperature Variability (CTV)	- Reflects spatial variability in water stress. - Identifies stress hotspots.	- Requires high-resolution temperature measurements. - Influenced by factors other than water stress.
Time-Temperature Threshold (TTT)	- Provides a threshold-based approach to assess stress. - Helps in understanding critical stress periods.	- Requires setting accurate temperature thresholds. - May not account for variability in crop types and growth stages.
Temperature Stress Day (TSD)	- Tracks the number of days with critical temperature stress. - Useful for assessing prolonged stress periods.	- Depends on accurate temperature data. - May need calibration for different crops and conditions
Degrees above Canopy Threshold (DACT)	- Provides a measure of how much temperature exceeds a threshold, indicating stress. - Can be tailored to specific crops or conditions	- Requires accurate canopy temperature thresholds. - May be affected by other environmental factors (e.g., humidity).
Water Deficit Index (WDI)	- Effectively integrated with remote sensing technologies, such as drones and satellites, facilitating large-scale and real-time monitoring of agricultural fields.	- Requires site-specific calibration for different crops, regions, and growth stages to ensure accurate assessment, which may require significant effort and expertise.

Several researchers have integrated thermal cameras into UAV platforms to evaluate crop water stress across entire fields. For example, [68] used canopy temperature characteristics derived from UAV thermal images to monitor cotton water status, finding a coefficient of determination (R^2) of 0.88 between canopy temperature standard deviation (CTSD) and stomatal conductance. Similarly, [37] assessed the potential of UAV thermal imaging for monitoring plant water stress in a commercial sugar beet field, demonstrating the robustness and reliability of a lightweight UAV canopy temperature system, despite some constraints related to weather conditions and area delimitation. To monitor crop water stress and its spatial variability at a field scale, researchers have developed Crop Water Stress Index (CWSI) maps using UAV remote-sensing systems. [6] characterized spatial variability in water status across vineyards with CWSI maps, effectively assessing water stress variability. [69] also evaluated cotton water stress and its spatial variability using a UAV thermal remote-sensing system, finding an R^2 of 0.84 between CWSI and leaf stomatal conductance in cotton fields in Yangling, Shaanxi, China. Numerous studies have incorporated thermal cameras into UAV systems to assess crop water stress over large fields. For instance [69] utilized canopy temperature data from UAV thermal imagery to monitor cotton water status, reporting a coefficient of determination (R^2) of 0.88 between the canopy temperature standard deviation (CTSD) and stomatal conductance. Similarly, [37] explored the use of UAV thermal imaging to track water stress in a commercial sugar beet field, showing that a lightweight UAV-based canopy temperature system was both robust and reliable, despite some limitations caused by weather conditions and field boundaries. To evaluate crop water stress and its spatial variability on a larger scale, researchers have developed Crop Water Stress Index (CWSI) maps using UAV remote-sensing technology. [6] successfully mapped water stress variability across vineyards using CWSI maps, while [68] analyzed cotton water stress and its spatial distribution, finding an R^2 of 0.84 between CWSI and leaf stomatal conductance in cotton fields in Yangling, Shaanxi, China.

5. Conclusion

Infrared thermography (IRT) is a vital tool in modern agriculture for monitoring water stress in fruit crops. Its non-invasive, real-time capabilities provide a comprehensive assessment of plant water needs, surpassing traditional methods like leaf water potential (LWP) and stomatal conductance. The Crop Water Stress Index (CWSI), which correlates canopy and ambient air temperatures, is particularly effective for fine-tuning irrigation schedules, helping farmers avoid over- or under-watering. However, environmental factors such as wind, solar radiation, and humidity must be considered for accurate results, and CWSI calibration is essential for specific crops. The future of IRT lies in integrating it with advanced technologies like UAVs, multispectral imaging, and IoT systems. These tools enable precise, large-scale water stress mapping and automated irrigation systems, improving water use efficiency and sustainability. Combining IRT with other data sources, such as multispectral imaging, offers a holistic approach to crop health and irrigation management, helping farmers optimize yields and conserve resources in response to global water challenges and climate change.

6. Future Scope

Future research should focus on developing low-cost, user-friendly infrared thermography systems integrated with AI-based decision support tools for real-time irrigation scheduling. Standardizing calibration protocols across diverse crops and environmental conditions is essential to improve accuracy and farmer adoption. Furthermore, integrating IRT with advanced remote sensing platforms such as multispectral imaging, satellite data, and soil moisture sensors will enhance the spatial and temporal resolution of water stress detection. Exploring machine learning algorithms for automated image processing and water stress classification can significantly accelerate data analysis. As climate change intensifies, leveraging IRT for proactive drought management will become increasingly critical in sustainable horticultural practices.

Conflict of Interest: Nill

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