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A Review of Recent Advances in Water Vapor Deficit Sensor Technology for Improving Plant Water Usage Efficiency

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ABSTRACT

Accurate assessment and monitoring of plant water stress are essential for optimizing irrigation strategies, improving water use efficiency. This article explores the multifaceted issue of water stress, encompassing both agricultural and environmental contexts. It emphasizes the pivotal role of precise water stress detection in effectively managing water resources and fostering sustainable agricultural practices. The primary focus is on the progression of sensors designed specifically to detect water stress, with particular attention given to two approaches: Vapor Pressure Deficit (VPD) and Crop Water Stress Index (CWSI). The article thoroughly investigates the underlying principles, operational mechanisms, advantages, and limitations of these sensor technologies. It vividly showcases their wide-ranging applications across agriculture, horticulture, and environmental monitoring, elucidating their significance in each domain. Moreover, it delves into the integration of VPD and CWSI sensors and introduces emerging technologies like thermal imaging and chlorophyll fluorescence sensors, expanding the horizon of water stress detection methodologies. Addressing the challenges linked to calibration and data interpretation, the article proposes potential pathways for future research endeavors. In essence, the overarching goal of this article is to propel the development of advanced sensor technologies, ultimately facilitating precise water stress detection. It aims to bolster sustainable water resource management practices while fortifying resilient agricultural methods in the face of evolving environmental challenges. VPD and CWSI-based approaches offer precise water stress insights in agriculture, aiding irrigation management.

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INTRODUCTION

The importance of water stress detection in agriculture and the challenges

Water stress is a critical factor that significantly impacts agricultural productivity and water management practices (Wang et al., 2023). The availability of water resources and efficient water use are vital for sustainable agriculture and ensuring food security. However, drought conditions and water scarcity pose significant challenges to crop growth and yield (Lei et al., 2016).

Accurate assessment and monitoring of plant water stress are essential for optimizing irrigation strategies, improving water use efficiency, and minimizing water wastage. Traditional methods of water stress detection, such as soil moisture sensors or plant-based indicators, have limitations in providing precise and real-time information on the water status of plants (González-Dugo et al., 2006).

Highlight the significance of VPD and CWSI-based approaches

In recent years, advancements in sensor technologies and data analytics have led to the development of innovative approaches for water stress detection. Two widely recognized approaches are based on VPD and CWSI (Testi et al., 2008). These approaches offer valuable insights into plant water status and aid in effective water management decisions.

VPD is a measure of the difference between the amount of moisture in the air and its maximum holding capacity at a specific temperature. It indicates the atmospheric demand for water and affects the rate of water loss from plants through transpiration. Temperature and VPD influence plant water requirements and transpiration rates. Higher temperatures increase evaporation rates, while a higher VPD leads to a higher transpiration rate. Understanding the relationship between temperature, VPD, and transpiration is crucial for managing water resources in agriculture and optimizing plant water use efficiency. Effective management of temperature and VPD can enhance plant growth, yield, and overall water use efficiency. Various studies have shown that temperature and VPD are primary drivers of transpiration in plants and influence their water requirements.

CWSI is a widely used indicator in agricultural studies to assess plant water stress levels. It represents the ratio of actual transpiration to potential transpiration and helps evaluate water availability for plant growth. When a plant transpires more water than it absorbs, it indicates water stress, which negatively impacts crop production, yield, and plant morphology.

The significance of VPD and CWSI-based approaches lies in their ability to provide accurate and real-time assessments of plant water stress. By incorporating environmental factors, plant physiological responses, and thermal information, these approaches offer a comprehensive understanding of the water status of crops.

This review article aims to explore the advancements in VPD and CWSI-based approaches for water stress detection in agriculture. It will delve into the principles, methodologies, and applications of these approaches, highlighting their benefits and challenges. The review will also discuss the potential of integrating VPD and CWSI-based approaches to enhance the accuracy and reliability of plant water stress assessment.

By providing a comprehensive overview of VPD and CWSI-based approaches, this review intends to contribute to the existing knowledge and promote the adoption of advanced sensor technologies for efficient water management in agriculture.

Table 1 provides a general overview of the three main categories of sensors: Soil Moisture Sensors, Leaf-Based Sensors, and Remote Sensing. It highlights the working principles, key advantages, disadvantages, and broad applications of each sensor type.

Table 1. general overview of the three main categories of sensors

Sensor Type	Working Principle	Pros	Cons	Applications
Soil Moisture Sensors	Tensiometers	- Direct measurement of soil moisture	- Requires installation and maintenance	- Agriculture, irrigation management
	Time Domain Reflectometry	- Accurate and non-destructive	- Sensitive to soil type and salinity	- Environmental monitoring, precision agriculture
	Capacitance-based sensors	- Easy to install and use	- Affected by soil compaction and temperature	- Agriculture, soil moisture monitoring
	Dielectric Sensors	- Non-invasive and real-time sensing	- Limited depth measurement range	- Agriculture, horticulture, hydrology
	Neutron Probe	- Direct measurement of soil moisture	- Expensive and requires expertise	- Research, agricultural management
Leaf-Based Sensors	Dendrometers	- Accurate measurement of plant growth	- Limited to woody plants	- Plant physiology, ecology, forestry
	Thermocouples	- Measures leaf temperature	- Requires direct contact with the leaf	- Environmental monitoring, crop research
	Stomatal Conductance	- Provides insights into plant water	- Requires calibration and expertise	- Plant physiology, water stress assessment
	Chlorophyll Fluorescence	- Measures plant stress and photosynthetic activity	- Requires dark adaptation of leaves	- Photosynthesis research, stress detection
	Leaf Nitrogen Sensors	- Quantifies leaf nitrogen content	- Calibration required for different species	- Agriculture, ecological studies, nutrient management
	Leaf Water Potential	- Measures plant water stress	- Invasive and destructive	- Water management, drought monitoring
Remote Sensing Technologies	Satellite imagery	- Large-scale coverage and data availability	- Limited spatial resolution	- Land cover mapping, climate studies
	Unmanned Aerial Vehicles (UAVs)	- High-resolution and flexible imaging	- Limited flight time and payload restrictions	- Agriculture, environmental monitoring
	Hyperspectral/Multispectral Imaging	- Detailed spectral information for land cover classification	- Data processing and interpretation complexity	- Agriculture, forestry, environmental monitoring

PRINCIPLES OF VPD AND CWSI

VPD and CWSI are two important concepts used in water stress assessment in plants. Understanding the principles behind VPD and CWSI is crucial for accurately evaluating and monitoring plant water status.

Vapor Pressure Deficit

VPD refers to the difference between the amount of moisture present in the air (actual vapor pressure) and the maximum amount of moisture the air can hold at a specific temperature (saturation vapor pressure). VPD represents the atmospheric demand for water and provides insights into the potential rate of water loss from plants through transpiration. Higher VPD values indicate higher water demand and potential for increased plant water stress (Allen et al., 1998).

The calculation of VPD involves the measurement of air temperature and relative humidity. The saturation vapor pressure is determined based on the temperature, and the actual vapor pressure is derived from the relative humidity. The difference between the saturation vapor pressure and the actual vapor pressure gives the VPD value (Idso et al., 1981).

Studies have shown that temperature and VPD are the primary drivers of transpiration in plants and influence their water requirements. VPD is also important for determining plant water needs. (Elbeltagi et al., 2023; Shekoofa et al., 2016; Yin et al., 2021). Saturated vapor pressure depends on temperature. For each Kelvin degree increase in the atmosphere, saturated vapor pressure approximately increases by 7% (Elbeltagi et al., 2023). High VPD indicates a dry environment, requiring plants to consume more water to obtain the needed amount of carbon dioxide.(Sinclair et al., 2017; Yin et al., 2021). VPD is determined from the following equation (Grossiord et al., 2020; Yin et al., 2021):

$$VPD = e_s - e_a = 0.6107 \times 10^{7.5\,T_{Leaf}/(273.3+T_{Leaf})} - RH \times \left((0.6107 \times 10^{7.5T_{air}/(273.3+T_{air})})/100\right) \quad (1)$$

Where, e_s is the saturated vapor pressure in the stomatal cavity at leaf temperature (kPa), e_a is the water vapor pressure of air at ambient temperature (kPa), RH is the relative humidity (%). According to the previous equation and the definition of VPD, the value of VPD depends on temperature and relative humidity. Most of the experimental studies that investigate the effects of VPD on vegetation also discuss other variables such as radiation, temperature and increasing atmospheric CO_2 concentration.

Water stress sensors based on VPD can be classified into different types, including psychrometers, hygrometers, and VPD-specific sensors. Psychrometers are traditional instruments that measure VPD by comparing temperature readings from wet-bulb and dry-bulb thermometers. Hygrometers are electronic sensors that measure relative humidity and temperature, enabling the calculation of VPD. VPD sensors directly measure VPD without additional calculations. These sensors combine temperature and humidity measurements to provide instant and accurate VPD readings.

Crop Water Stress Index

The CWSI is a quantitative indicator that integrates thermal and vegetation-related parameters to assess the water stress levels of crops. CWSI combines information from infrared thermography, remote sensing data, and mathematical algorithms to estimate plant water stress.

CWSI is based on the principle that water-stressed plants tend to have higher leaf temperatures compared to well-watered plants due to reduced transpiration. It utilizes thermal imagery to capture the temperature differences, and vegetation indices (such as normalized difference vegetation index, NDVI) to account for variations in plant cover and biomass (Jones, 2004).

CWSI is a measure of water stress in plants, indicating the ratio of actual transpiration to potential transpiration. Adequate water availability is crucial for optimal plant activities, and water stress can lead to physiological changes and reduced crop productivity. CWSI is calculated based on transpiration rates, with higher values indicating increased water stress (Jackson et al., 1981). High CWSI values can result in decreased photosynthesis, wilting, reduced growth, and lower crop yields. Monitoring CWSI helps in making informed decisions about irrigation and water management strategies. Effective irrigation practices and maintaining optimal soil moisture levels are essential to mitigate water stress and enhance agricultural productivity in water-limited environments (Kizer et al., 2017).

$$CWSI = \frac{(T_{leaf} - T_{air})_{observed} - (T_{leaf} - T_{air})_{sat}}{(T_{leaf} - T_{air})_{sat} - (T_{leaf} - T_{air})_{dry}} \quad (2)$$

CWSI is a quantitative index that combines thermal and vegetation-related parameters to assess plant water stress. It utilizes infrared thermography, remote sensing data, and mathematical algorithms to estimate the water stress levels of crops. CWSI provides a holistic view of plant water status, considering both the physiological response and thermal characteristics of plants.

CWSI varies from zero to one. A value of zero indicates a plant without water stress. In contrast, a plant with a CWSI of 1 under severe water deficit conditions (no transpiration) (Kizer et al., 2017; Paulo et al., 2023). Another method to determine the CWSI is presented by Idso (1982) (the non-water-stressed baseline equation (NWSB):

$$CWSI = \frac{(T_{leaf} - T_{air}) - (T_{leaf} - T_{air})_{LL}}{(T_{leaf} - T_{air})_{UL} - (T_{leaf} - T_{air})_{LL}} \quad (3)$$

Where, $(T_{leaf} - T_{air})_{LL}$, $(T_{leaf} - T_{air})_{UL}$ and $(T_{leaf} - T_{air})$ are the lower limit, the upper limit (in no transpiration)and the difference of air temperature and leaf surface (℃).The parameters of the NBWS equation are different for vary crops and relates the difference between leaf and ambient temperature to VPD. As the VPD increases due to an increase in air temperature or a decrease in atmospheric water vapor pressure, the product temperature becomes cooler than the air temperature. Jackson et al. (1988) declared this method ineffective due to the influence of changes in wind speed and solar irradiance. Also, O'Toole and Real (1986) stated that due to wind fluctuations there is a poor agreement between the experimentally estimated upper limit and the measured values in crops under severe water stress

Both VPD and CWSI are valuable tools for assessing plant water stress. VPD provides information on the atmospheric demand for water, while CWSI combines thermal and vegetation data to estimate plant water stress levels. Understanding the principles and calculations involved in determining VPD and CWSI values enables researchers and practitioners to accurately evaluate and monitor water stress in agricultural systems. These concepts play a significant role in enhancing water management practices, optimizing irrigation strategies, and improving crop productivity in water-limited environments.

VPD-BASED SENSORS

Various sensor employed in VPD-based

Various sensor technologies and methodologies are used for VPD-based water stress detection. These include vapor pressure sensors, psychrometric sensors, humidity sensors, weather stations, remote sensing, and integrated sensor systems. These sensors measure parameters such as vapor pressure, temperature, humidity, and vegetation indices to calculate VPD. They are used in research, commercial applications, weather monitoring, and environmental monitoring to assess plant water stress and monitor water stress patterns over time (Lee and Lee, 2005).

It is important to note that the choice of sensor technology depends on the specific requirements of the application, the level of accuracy needed, and the available resources. Researchers and practitioners should carefully evaluate the suitability of each sensor technology for their intended use and consider factors such as cost, maintenance, and data compatibility.

The advancements and limitations of VPD-based sensors

VPD data analysis involves applying statistical techniques, time series analysis, machine learning algorithms, geospatial analysis, data fusion methods, and model development. These approaches help summarize VPD data, identify trends, assess relationships with other variables, analyze temporal patterns, predict water stress levels, integrate spatial information, improve data accuracy, and simulate VPD based on environmental factors. By utilizing these methodologies, a comprehensive understanding of VPD and its implications for assessing plant water stress and environmental conditions can be achieved.

The specific choice of methodology and algorithm depends on the research objectives, data characteristics, and the level of complexity desired in the analysis. Researchers may employ a combination of these techniques to gain comprehensive insights into the VPD data and its relationship with plant water stress.

Advantages of VPD-based sensors include:

VPD sensors offer several advantages for water stress detection:

1. Direct measurement of transpiration driving force
2. Non-destructive nature
3. Sensitivity to plant water stress
4. Compatibility with various crop types.

To enhance VPD sensor capabilities, the following approaches are utilized:

1. Integration of weather data for more accurate measurements
2. Utilization of remote sensing for spatially explicit information
3. Application of machine learning algorithms for improved water stress detection
4. Development of smart sensor networks for real-time monitoring and data analysis

These advancements have made VPD sensors more sophisticated, accurate, and accessible tools for water stress detection, enabling better management of plant water stress in agricultural and environmental applications.

Limitations of VPD-based sensors include:

VPD-based sensors used for water stress assessment have limitations that should be considered:

1. Sensitivity to environmental factors, such as temperature and humidity, can affect VPD measurements and lead to inaccuracies. Proper calibration and accounting for environmental conditions are necessary for accurate results.
2. Calibration and validation are essential to ensure the accuracy and reliability of VPD sensors. Comparisons with reference measurements and verification under different conditions help validate their performance.
3. Lack of species-specific calibration can introduce uncertainties in interpreting VPD measurements for different plant types. Specific calibration for different species is important for reliable water stress assessment.
4. Canopy structure, including leaf density and arrangement, can influence VPD measurements within the canopy. Variations in canopy structure among plant species or growth stages can affect the interpretation of VPD data, especially in complex canopies.

By addressing these limitations through proper calibration, validation, accounting for environmental factors, and considering canopy structure, the accuracy and reliability of VPD-based sensors can be enhanced for effective water stress assessment.

Case studies and applications

The VPD is a measure of the difference between the amount of moisture in the air and the maximum amount of moisture the air can hold at a particular temperature. It is commonly used in agriculture, horticulture, and environmental science to assess plant water stress and determine optimal growing conditions. Here are some case studies and applications of VPD:

1. Crop Growth and Yield Optimization: VPD is used to optimize crop growth and yield by maintaining an ideal balance of water uptake and transpiration. Studies have shown that maintaining VPD within a specific range can enhance plant physiological processes, such as photosynthesis and stomatal regulation, leading to improved crop performance and productivity.

2. Greenhouse and Controlled Environment Agriculture: VPD is closely monitored in controlled environments like greenhouses to create optimal growing conditions for plants. By adjusting temperature, humidity, and ventilation, growers can manipulate VPD levels to promote healthy plant growth, prevent diseases, and optimize resource use efficiency.

3. Irrigation Management: VPD is used as a tool to determine when and how much to irrigate crops. By considering VPD values alongside other factors like soil moisture and plant water

requirements, farmers can schedule irrigation to ensure plants receive adequate water without causing water stress or excessive water loss through transpiration.

4. Plant Stress Diagnosis: VPD is used as an indicator of plant stress and can help identify water stress, heat stress, or other environmental imbalances. Monitoring VPD levels allows growers to take corrective actions such as adjusting irrigation, providing shade, or implementing cooling strategies to mitigate stress and maintain plant health.

5. Pest and Disease Management: VPD can influence the susceptibility of plants to pests and diseases. By understanding the relationship between VPD and specific pests or diseases, farmers can implement preventive measures, such as adjusting humidity levels or optimizing plant spacing, to minimize the risk of infestation or infection.

6. Environmental Monitoring and Research: VPD is used in environmental research to assess ecosystem water availability, drought stress, and climate change impacts on vegetation. Monitoring VPD levels helps scientists understand plant responses to changing environmental conditions and develop strategies for sustainable resource management.

These are just a few examples of how VPD is applied in various fields. The specific applications and case studies may vary depending on the context, crop type, and research objectives.

The advancement of sensor technologies and data-driven approaches has revolutionized the monitoring and management of plant water stress, leading to improved irrigation strategies and enhanced agricultural sustainability. This text discusses recent studies that highlight the potential of these technologies in providing accurate and continuous monitoring of plant physiological parameters, such as VPD, stem water potential (SWP), and CWSI.

Below are some studies that actually show the potential of sensor technologies, machine learning and remote sensing in monitoring and managing plant water stress, optimizing irrigation strategies and enhancing agricultural sustainability.

Tomato water status estimation using photochemical reflectance index (PRI) and machine learning was investigated. Proximal sensors and UAV imagery were utilized for efficient monitoring (Fig. 1) (Tang et al., 2023). Random forest regression models were developed based on data from an experimental tomato field in California. The models integrated PRI, vegetation indices, and weather data to estimate tomato stem water potential (ψ stem). The proximal sensor-based model achieved an R2 of 0.74 and a mean absolute error (MAE) of 0.63 bars. The UAV-based model had an R2 of 0.81 and MAE of 0.67 bars. PRI emerged as the most important variable in both models. This study demonstrates the potential of machine learning and remote sensing for data-driven irrigation management of processing tomatoes.

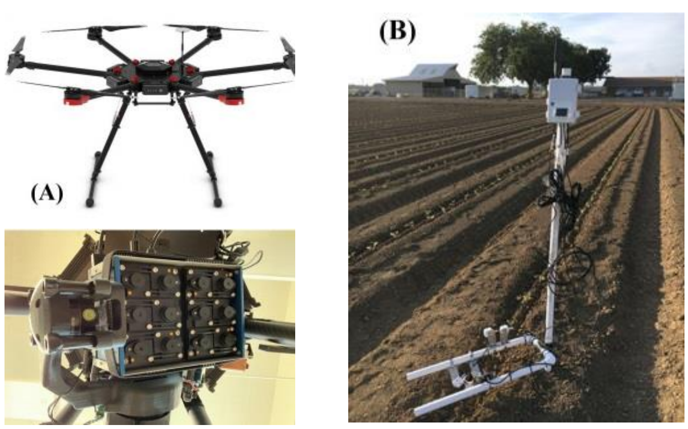

Fig 1. (A) UAV and multispectral camera were employed in this study.(B) Stands in the field were equipped with proximal sensors, Adapted from Tang et al. (2023).

A study focuses on forecasting VPD for agricultural water management in semi-arid environments. Machine learning algorithms were used to model VPD in eight regions in Egypt (Paulo et al., 2023). The Random Forest (RF) model performed the best in terms of statistical measures. VPD is crucial for plant physiology and water demand, and its increase can affect evapotranspiration and plant productivity. The study highlights the importance of VPD prediction for water management and climate adaptation. It also emphasizes the challenges in obtaining reliable weather data in developing countries. The findings contribute to directing future research and policymakers' attention to VPD's influence on the hydrological cycle. The study is relevant for addressing water shortages and achieving agricultural sustainability in Egypt amid climate change.

A study entitled 'dependence of CWSI-based plant water stress estimation with diurnal acquisition times in a nectarine orchard.' It was crowded (Park et al., 2021). This study focused on the dependence of plant water stress estimation using the CWSI on different acquisition times during the day in a nectarine orchard. UAV-borne thermography was used to monitor crop water status in real-time for precise irrigation scheduling. The CWSI values, derived using the Adaptive CWSI method, were compared with plant physiological parameters such as stem water potential (ψ_{stem}) and stomatal conductance (g_s). Results showed a strong relationship between ψ_{stem} measurements and CWSI values at midday. Diurnal CWSI values correlated significantly with g_s across different irrigation levels and time points. The study suggests that UAV-borne thermography between mid-morning and mid-afternoon can effectively map plant water stress, expanding the time window for accurate assessment.

Yin et al. (2021) discusses the development of a wearable leaf sensor for continuous monitoring of vapor-pressure deficit (VPD) in plants (Fig. 2). The sensor integrates a graphene-based relative humidity (RH) sensing element and a gold-based thin-film thermistor on a flexible polyimide sheet, allowing accurate and continuous determination of VPD at the leaf surface. By attaching multiple sensors to different locations on a plant, the time required for water transport from the roots to each measured leaf and longitudinally within a leaf can be estimated. The sensor was validated in a greenhouse experiment, where it successfully monitored leaf RH and temperature of maize plants over a period of more than 2 weeks, and demonstrated the influences of light and irrigation on maize transpiration. Additionally, the sensor was deployed in crop production fields and showed the ability to detect differences in transpiration between fertilized and unfertilized maize plants. The wearable leaf sensor provides valuable information on plant transpiration, which can aid in managing growth environments for optimal water and nutrient use efficiencies and improving disease control. The sensor's flexible and conformable nature, along with its accurate and continuous monitoring capabilities, make it a promising tool for studying plant physiology and optimizing crop production.

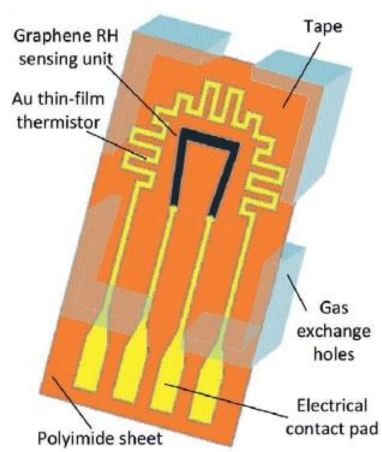

Fig 2. Illustration of the integrated temperature and humidity sensor fabricated on a flexible substrate. The sensor comprises a thin-film gold temperature sensor and a humidity (RH) sensor based on laser-induced graphene, Adapted from Yin et al. (2021).

A mobile sensor suite was developed and evaluated to detect plant water stress by measuring leaf temperature and microclimatic variables in almond, walnut, and grape crops

(Dhillon et al., 2014). The sensor suite showed successful results in commercial orchards, with high coefficient of determination values for shaded leaf temperature. Stem water potential (SWP) was found to be a significant variable in all models. The sensor suite was also used to classify trees into water stressed and unstressed categories with relatively low misclassification errors. This research demonstrates the feasibility of using the sensor suite for irrigation management in nut and vineyard crops (Fig. 3).

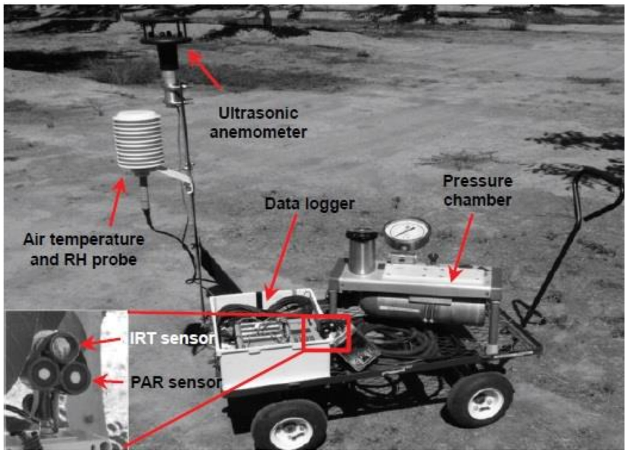

Fig 3. During a data collection event, a mobile sensor suite and a pressure chamber were deployed, Adapted from Dhillon et al. (2014)

These studies collectively demonstrate the potential of sensor technologies, machine learning, and remote sensing in monitoring and managing plant water stress, optimizing irrigation strategies, and fostering agricultural sustainability. By providing real-time and accurate information, these advancements contribute to more efficient water use, enhanced crop productivity, and informed decision-making in precision agriculture. Summarizing the key information from the provided studies is given in Table 2.

Table 2. Summary of Studies on Plant Water Stress Monitoring and Management

Study	Focus	Methodology	Findings
(Tang et al., 2023)	Estimation of tomato water status using PRI and machine learning	Proximal sensors and UAV imagery	Developed regression models based on PRI, achieved accurate estimation of tomato stem water potential, potential for data-driven irrigation management of processing tomatoes
(Paulo et al., 2023)	Forecasting VPD for agricultural water management	Machine learning algorithms, RF model	RF model performed best in predicting VPD, importance for plant physiology and water demand, relevance for water management and climate adaptation
(Park et al., 2021)	Dependence of CWSI-based plant water stress estimation on acquisition times	UAV-borne thermography	Strong correlation between CWSI values and physiological parameters, effective mapping of water stress with mid-morning to mid-afternoon acquisition times
(Yin et al., 2021)	Wearable leaf sensor for continuous monitoring of VPD	Graphene-based RH sensing element and thin-film thermistor	Successfully monitored leaf RH and temperature, influenced by light and irrigation, valuable for managing growth environments and optimizing crop production
(Dhillon et al., 2014)	Mobile sensor suite for detecting plant water stress	Measurement of leaf temperature and microclimatic variables	Effective in commercial orchards, high accuracy in classifying trees into stressed and unstressed categories, potential for irrigation management in nut and vineyard crops

This table provides a concise overview of the studies, including their focus, methodology, and main findings, highlighting the advancements in monitoring plant water stress and their potential applications in agricultural management.

CWSI-BASED SENSORS

CWSI is a widely used indicator for assessing plant water stress. Various sensor technologies and approaches have been developed to estimate CWSI and monitor plant water status accurately. These sensors play a crucial role in providing real-time data for efficient irrigation management and optimizing water use in agriculture.

A study focuses on implementing a continuous leaf monitoring system in almond orchards to enable precision irrigation (Kizer et al., 2017). The leaf monitor measures leaf temperature and other microclimatic variables to calculate a CWSI. The system utilizes a wireless mesh network for remote data reporting and irrigation control. Fourteen leaf monitors were interconnected in a 4-acre almond orchard, and irrigation was scheduled independently in two management zones based on soil and plant characteristics. The CWSI values were continuously used to guide irrigation decisions, resulting in water savings and increased water productivity. The study concludes that precision irrigation using the leaf monitoring system is a valuable tool for irrigation scheduling and water savings in almonds.

Sensor Technologies

Thermal Imaging: Thermal cameras or infrared thermography sensors are commonly used for CWSI estimation. These sensors capture the thermal radiation emitted by plants, which is influenced by their water status. By measuring the temperature of plant canopies, thermal imaging allows for the calculation of CWSI. CWSI has long been recognized as a reliable metric for assessing crop water stress, which in thermal Imaging method is characterized by (Jackson et al., 1981):

$$CWSI = \frac{T_{canopy} - T_{wet}}{T_{dry} - T_{wet}} \tag{4}$$

Where the average temperature of the canopy is T_{canopy}, the temperatures of reference surfaces that represent maximum (Twet) and minimum (Tdry) leaf transpiration under the prevailing environmental conditions. Thermal imagery offers a reliable and non-invasive method to capture temperature variations.

Infrared Thermometry: Infrared thermometers are handheld devices that measure the temperature of individual leaves or canopies. These measurements are used to calculate CWSI based on the temperature differences between plant tissues and reference conditions.

Sap Flow Sensors: Sap flow sensors measure the rate of sap movement within plant stems. By monitoring sap flow, which is influenced by water availability, CWSI can be estimated.

CWSI Estimation Techniques

- **Baseline Methods**: Baseline methods involve comparing the actual plant temperature with a reference temperature under non-water-stressed conditions. The temperature difference is then used to calculate CWSI.

- **Temperature Difference Methods:** These methods calculate CWSI by considering the temperature difference between plant canopies and reference areas.

- **Energy Balance Models:** Energy balance models use multiple parameters, including air temperature, net radiation, and wind speed, to estimate CWSI.

- **Vegetation Indices:** Vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), can be used in conjunction with temperature measurements to estimate CWSI.

4.3. Case Studies and Applications

Below are summaries of several research studies that explore various techniques and methodologies for monitoring water stress and drought conditions using remote sensing, sap flow measurements, infrared thermometry, and crop water stress indices:

Zhang et al. (2023) explored the use of CWSI to monitor water stress in maize. Researchers compared empirical (CWSI_E) and theoretical (CWSI_T) methods and examined their response to environmental factors and growth stages. They found that both methods were effective when VPD values exceeded 1.5 kPa. Both CWSI_E and CWSI_T accurately tracked maize water stress and correlated well with sap flow measurements. They also successfully predicted grain yield and water use efficiency. The study emphasizes the importance of accurate crop water status estimation for efficient irrigation management and suggests the need for further research on CWSI baselines, environmental criteria, and critical values.

A custom, portable drill press was tested to address the issue of probe misalignment in sap flow sensors. Misalignment of sap flow probes can lead to errors in measuring plant transpiration. The study compared the drill press with two drilling templates in terms of misalignment errors in laboratory and field settings. The results showed that the drill press was the most effective method, ensuring parallel drill holes even at greater depths. Field installations using the drill press had no misalignment issues, while a significant number of holes drilled with templates required re-drilling. The widespread use of the portable drill press would minimize alignment uncertainty and improve the accuracy of sap flow measurements, facilitating a better understanding of transpiration and its influencing factors (Beslity and Shaw, 2023).

A study examined the effects of water stress on grapevines and evaluated various physiological indicators to assess their water status. The experiment involved subjecting potted grapevines to two drought cycles. When water stress was not present, transpiration rates were influenced by environmental factors. However, under water stress, transpiration was significantly reduced, indicating impaired stomatal functioning. Sap flow measurements underestimated actual transpiration. At the end of the second drought cycle, vines exhibited incomplete physiological recovery and carryover stress effects from the first cycle. The study emphasizes the need for accurate indicators to manage irrigation strategies in viticulture and highlights the importance of integrating multiple physiological indices to understand grapevine responses to water stress (Benyahia et al., 2023).

Dukat et al. (2023) examined the response of Scots pine trees to drought in north-western Poland using eddy covariance (EC) and sap flow methods. The researchers compared transpiration estimates from these two methods and analyzed the relationship between sap flow and soil water content (SWC). They found that sap flow-based transpiration was significantly lower than EC-derived transpiration during a severe drought in 2019. The presence of understory vegetation in the mature stand may have contributed to this difference. The study also revealed a threshold at which sap flow sharply decreased, indicating stomatal closure, but non-stomatal factors likely influenced water conductivity. The findings highlight the importance of accurate transpiration estimation and considering non-stomatal water losses during extreme dry conditions. The research contributes to understanding drought impact on forest ecosystems and has implications for water management and predicting forest response to drought stress, particularly for Scots pine forests in the area.

A paper presents the development of a low-cost water stress detection system using infrared (IR) sensors and image processing. The system uses leaf temperature indices obtained from IR sensor readings and image segmentation to measure plant temperature, generate thermal maps, and identify water stress conditions. The results showed that the low-cost IR sensors can effectively measure plant temperature and provide accurate thermal maps. The estimated CWSI obtained from the system is consistent with literature results. The system offers a cost-effective alternative to expensive thermal cameras for detecting and monitoring crop water stress in precision irrigation (Paulo et al., 2023).

Zhou et al. (2021) discussed assessing crop water stress using infrared thermal imagery in precision agriculture: a comprehensive review and promising future with deep learning. This review paper examines the use of infrared thermal imagery for assessing crop water stress in precision agriculture. It discusses the technology involved, including uncooled thermal cameras and platforms like ground-based and unmanned aerial vehicles (UAVs) for image acquisition. The paper also explores canopy segmentation strategies and the correlation between different forms of the CWSI and physiological indicators. The advantages of uncooled thermal cameras are highlighted, along with the benefits and limitations of ground-based and UAV-based platforms. The future prospects of using deep learning approaches for crop water stress assessment are discussed, noting advancements in technology that can overcome current challenges. Overall, the paper provides a comprehensive overview of using infrared thermal imagery for crop water stress assessment, emphasizing the potential for future developments in precision agriculture.

In a study, CWSI was evaluated based on leaf temperature to detect water deficiency in greenhouse grapes (Ru et al., 2020). Various parameters, including meteorological factors, soil moisture, leaf temperature, growth indicators, and physiological indicators, were studied. The results showed a significant relationship between the leaf-air temperature difference (Tc-Ta) and plant water status indicators, with stomatal conductance and transpiration rate having the closest relationship. CWSI values were more easily observed on sunny days, and a specific observation time was identified as optimal for CWSI values. A reliable linear correlation was found between CWSI values and soil moisture at 0-40 cm depth. Overall, the study concluded that CWSI based on leaf temperature is a practical and accurate method for monitoring grapevine water status in greenhouses, which can improve irrigation management and enhance grapevine growth and productivity.

A study aimed to assess the water status of grapefruit trees under saline reclaimed water and deficit irrigation using infrared thermometry. The results showed positive differences between canopy temperature (Tc) and air temperature (Ta) across varying VPDs. Non-Water Stressed Baselines (NWSBs) were established by correlating Tc-Ta with VPD, showing diurnal and seasonal variations influenced by solar radiation and zenith solar angle (θ_Z). The CWSI, calculated based on Tc-Ta, exhibited strong agreement with stem water potential and proved to be the most suitable thermal indicator. The study highlights the effectiveness of infrared thermometry in assessing water stress and offers insights for water-saving irrigation strategies in citrus cultivation under challenging water conditions (Romero-Trigueros et al., 2019).

A study comparing three CWSI models with sap flow measurements in maize was conducted (Han et al., 2018). This study compared three CWSI models with sap flow measurements in maize to assess their accuracy, limitations, and uncertainties. The models included an empirical model (CWSI-E) and two theoretical models: one using calculated aerodynamic resistance (CWSI-T1) and the other using seasonal average aerodynamic resistance (CWSI-T2). The results showed that considering the uncertainty of crop coefficient and sap flow measurement, both CWSI-T2 and CWSI-E models provided reasonable estimates of water stress.

Sensor technologies play a crucial role in assessing and monitoring water stress in plants and crops. Infrared thermal imagery, combined with deep learning, shows promise in precision agriculture for evaluating crop water stress. Low-cost infrared sensors and image processing techniques offer an affordable alternative for detecting water stress conditions. Infrared thermometry proves effective in assessing water stress in citrus cultivation and grapevines under challenging water conditions. Guidelines are provided for accurate canopy temperature measurements using infrared thermometers. The CWSI is widely used for monitoring water stress in crops and exhibits responsiveness to environmental factors and growth stages. Integrating multiple physiological indicators is crucial for effective irrigation management in viticulture. The use of a portable drill press improves the accuracy of sap flow measurements by minimizing probe misalignment. Comparisons between sap flow and eddy covariance methods highlight the importance of accurate transpiration estimation, considering non-stomatal water losses during severe drought conditions. These advancements in sensor technologies and methodologies contribute to a better understanding of water stress, enabling efficient irrigation management and predicting plant responses to drought stress. **Table 3** The table below provides a concise summary of key research articles focused on water stress detection and drought monitoring, covering topics such as remote sensing models, sap flow measurements, infrared thermometry, and crop water stress indices.

Table 3. Summary of Key Research Articles on Water Stress Detection and Drought Monitoring Methods

Study	Main Focus
(Zhang et al., 2023)	Examines the use of CWSI for maize water stress Compares empirical (CWSI_E) and theoretical (CWSI_T) methods Evaluates response to environmental factors and growth stages Emphasizes accurate crop water status estimation and further research needs
(Beslity and Shaw, 2023)	Tests a portable drill press to address probe misalignment in sap flow sensors Compares with drilling templates in laboratory and field settings Demonstrates effectiveness in minimizing misalignment and improving accuracy
(Benyahia et al., 2023)	Examines water stress effects on grapevines and physiological indicators Subjects' grapevines to drought cycles and measures transpiration Highlights impaired stomatal functioning, incomplete recovery, and indicators
(Dukat et al., 2023)	Studies Scots pine response to drought using eddy covariance and sap flow Compares transpiration estimates and analyzes sap flow and soil water content Discusses stomatal closure, non-stomatal factors, and implications
(Paulo et al., 2023)	Develops a low-cost water stress detection system using infrared sensors Measures plant temperature and generates thermal maps for stress identification Validates CWSI estimation using the system
(Zhou et al., 2021)	Reviews the use of infrared thermal imagery for crop water stress assessment Examines technology, platforms, segmentation strategies, and correlations Discusses advantages, limitations, and future prospects, including deep learning
(Ru et al., 2020)	Evaluates the CWSI based on leaf temperature Studies the relationship with plant water status and soil moisture Identifies optimal observation time and practicality for greenhouse grapes
(Romero-Trigueros et al., 2019)	Assesses water status of grapefruit trees using infrared thermometry Establishes non-water stressed baselines and calculates CWSI Correlates with stem water potential and suggests water-saving strategies
(Han et al., 2018)	Compares three CWSI models with sap flow Evaluates accuracy, limitations, and uncertainties of the models

These research articles contribute valuable insights to the field of water stress detection and drought monitoring, providing a foundation for developing effective strategies to manage water resources in agricultural and ecological settings.

Integration of VPD and CWSI

The integration of VPD and CWSI approaches holds promise for improving water stress detection and management in agricultural systems. Here are key points to consider when discussing the integration of VPD and CWSI:

Benefits and Challenges

- Improved Accuracy: Integrating VPD and CWSI provides a more comprehensive understanding of plant water stress by considering both atmospheric demand (VPD) and plant response (CWSI).

- Enhanced Precision: The combined use of VPD and CWSI allows for a more nuanced and accurate assessment of plant water stress across different environmental conditions and crop types.

- Water Management Efficiency: Integrating VPD and CWSI can lead to improved irrigation scheduling and water conservation strategies, optimizing water use efficiency in agriculture.

- Data Requirements: Integrating VPD and CWSI requires access to meteorological data (for VPD calculation) and remote sensing or thermal imaging data (for CWSI calculation), which may pose challenges in terms of data availability and processing.

Synergies and Future Directions

- Synergistic Effects: Integrating VPD and CWSI can provide a more comprehensive understanding of the complex interactions between atmospheric conditions and plant water status, leading to improved water stress assessment.

- Advanced Modeling: Future research can focus on developing advanced modeling approaches that incorporate both VPD and CWSI to enhance water stress predictions and optimize irrigation strategies.

- Sensor Technologies: Advances in sensor technologies, such as the integration of weather stations and thermal cameras, can facilitate the simultaneous measurement of VPD and CWSI, enabling real-time monitoring and decision-making.

- Data Fusion Techniques: Integrating multi-source data, including satellite imagery, weather data, and ground-based measurements, through data fusion techniques can further enhance the integration of VPD and CWSI.

In conclusion, the integration of VPD and CWSI approaches offers valuable insights into plant water stress assessment and irrigation management. The combined use of these approaches improves accuracy, enhances precision, and contributes to more efficient water resource management in agriculture. Future research and technological advancements will continue to refine the integration of VPD and CWSI, enabling more effective water stress detection and sustainable agricultural practices.

ADVANCEMENTS AND INNOVATIONS

The field of water stress detection has witnessed significant advancements in sensor technologies, data analytics, and modeling techniques. Here are key points to consider when discussing recent advancements and innovations in the context of VPD and CWSI-based sensors:

Sensor Technologies

- Wireless Sensor Networks (WSNs): WSNs have revolutionized the field of water stress detection by enabling real-time monitoring of environmental variables, including VPD and CWSI. These networks consist of spatially distributed sensors that communicate wirelessly, providing continuous data collection and analysis.

- Internet of Things (IoT): The integration of IoT with water stress sensors allows for seamless connectivity and data transmission, enabling remote monitoring and control of irrigation systems. IoT-based sensors can provide real-time VPD and CWSI measurements, facilitating precise water stress assessment.

- Hyperspectral Sensors: Hyperspectral sensors capture spectral information across a wide range of wavelengths, enabling detailed analysis of plant physiological parameters. These sensors can be used to derive spectral indices related to water stress, complementing VPD and CWSI-based approaches.

Data Analytics and Modeling Techniques

- Artificial Intelligence (AI): AI techniques, such as machine learning and deep learning algorithms, have shown promise in water stress detection. These approaches can analyze large volumes of data, including VPD, CWSI, and other relevant variables, to identify patterns and make accurate predictions.

- Data Fusion: Data fusion techniques combine information from multiple sources, such as satellite imagery, weather data, and ground-based measurements, to enhance water stress assessment. Fusion of VPD and CWSI data with other relevant datasets can provide a more comprehensive understanding of plant water status.

- Spatial Modeling: Spatial modeling techniques, such as Geographic Information Systems (GIS), enable the integration of geospatial data with VPD and CWSI measurements. This integration allows for spatially explicit mapping of water stress conditions and targeted irrigation management.

Emerging Trends

- Precision Agriculture: The integration of VPD and CWSI-based sensors with precision agriculture technologies, such as variable rate irrigation and automated irrigation systems, enables site-specific irrigation management, maximizing water use efficiency and crop productivity.

- Remote Sensing: Remote sensing platforms, including satellites and unmanned aerial vehicles (UAVs), provide valuable data for VPD and CWSI estimation at large spatial scales. These platforms can capture multispectral and thermal imagery, allowing for remote monitoring of water stress conditions over extensive agricultural areas.

- Sensor Miniaturization: Ongoing advancements in sensor miniaturization have led to the development of compact, low-cost VPD and CWSI sensors. These portable sensors facilitate easy deployment and widespread adoption in various agricultural settings.

In conclusion, recent advancements in sensor technologies, data analytics, and modeling techniques have significantly enhanced water stress detection. The integration of VPD and CWSI-based sensors with emerging trends, such as wireless sensor networks, IoT, AI, and remote sensing, opens new avenues for precise and efficient water stress assessment in agriculture. Continued research and innovation in these areas will drive further advancements and promote sustainable water management practices.

METHODOLOGY SECTION

Physically-based models: - Advantages: Incorporate fundamental principles of heat and mass transfer, provide detailed insights into plant-water interactions. - Disadvantages: Require extensive input data and parameterization, may be computationally intensive. - Key findings: Physically-based models have shown good performance in capturing plant water stress dynamics and predicting water status under different environmental conditions.

Statistical models - Advantages: Relatively simple and efficient, require less input data, can handle large datasets. - Disadvantages: May lack mechanistic understanding, assumptions about data distribution may limit applicability. - Key findings: Statistical models have demonstrated good accuracy in predicting water stress levels based on easily measurable variables such as weather data and plant physiological parameters.

Artificial intelligence (AI) models - Advantages: Ability to learn complex patterns, handle nonlinear relationships, adapt to changing conditions. - Disadvantages: Require large training datasets, may be prone to overfitting, lack interpretability. - Key findings: AI models, such as neural networks and machine learning algorithms, have shown promising results in water stress detection, achieving high accuracy and robustness.

Remote sensing models - Advantages: Provide spatial and temporal information, non-destructive and scalable, useful for large-scale monitoring. - Disadvantages: Limited ground-level validation, sensitivity to atmospheric conditions, dependence on satellite availability. - Key findings: Remote sensing-based models, utilizing satellite imagery and vegetation indices, have demonstrated the capability to assess water stress over large areas and monitor crop health.

Some articles related to advances in remote sensing for water stress detection and drought monitoring are listed below:

Allen et al. (2007) studied satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)—Model. This article introduces the METRIC model, which is a remote sensing-based model used to estimate evapotranspiration. It provides a detailed description of the principles and algorithms employed by the model. METRIC utilizes satellite imagery to derive essential parameters related to energy balance and vegetation water stress, enabling accurate estimation of evapotranspiration.

Senay et al. (2013) reviewed operational evapotranspiration mapping using remote sensing and weather datasets. This article offers a comprehensive review of remote sensing-based models for estimating actual evapotranspiration. It provides an overview of different approaches, algorithms, and satellite data sources used in these models. The review discusses the strengths and limitations of various techniques, allowing researchers and practitioners to select appropriate methods for their specific applications.

Bajgiran et al. (2008) used AVHRR-based vegetation indices for drought monitoring in the Northwest of Iran. This study assesses the suitability of NOAA-AVHRR data for drought monitoring in a cold semi-arid region of northwest Iran. The researchers examined the correlation between satellite-derived vegetation indices (NDVI and VCI) and precipitation data to detect drought conditions. They processed AVHRR images, calculated NDVI and VCI, and collected precipitation statistics from meteorological stations over a five-year period. The results showed a strong correlation between NDVI and precipitation, indicating that NDVI can effectively reflect precipitation fluctuations and provide early awareness of drought for better drought risk management. This study demonstrates the potential of remote sensing data in drought monitoring and management.

A comprehensive assessment of remote sensing and traditional based drought monitoring indices at global and regional scale was provided (Alahacoon and Edirisinghe, 2022) . This article provides a comprehensive assessment of drought monitoring indices, focusing on both traditional and remote sensing-based approaches. The study reviews 111 indices, categorizing them into traditional and remote sensing categories. It finds that meteorological drought monitoring has the highest number of traditional indices, while remote sensing-based indices are primarily used for agricultural drought monitoring. The article emphasizes the advancements in satellite technology, which have facilitated the development of new remote sensing-based indices and improved spatial distribution and resolution calculations. Overall, the study highlights the significance of drought indices in quantifying drought severity and impact, and the potential of remote sensing for more effective drought monitoring.

Farhan and Al-Bakri (2019) discuss the use of remote sensing and geospatial techniques to monitor and assess drought in Jordan. It explores the correlations between drought indices derived from remote sensing data and soil moisture measurements. The study recommends the adoption of these remote sensing indices for monitoring and mapping agricultural droughts in the region. Overall, the article highlights the importance of utilizing advanced technology for effective drought monitoring and emphasizes the potential of remote sensing in this field.

These articles focus on remote sensing models and techniques for water stress detection. They cover topics such as estimating evapotranspiration, monitoring vegetation water stress, assessing drought conditions, and utilizing various remote sensing data sources and algorithms. The articles provide insights into the application, strengths, and limitations of remote sensing models for water stress detection and drought monitoring. A summary of the mentioned articles is given in **Table 4**.

Table 4. Advances in remote sensing for water stress detection and drought monitoring

Study	Main Focus
(Allen et al., 2007)	Introduces the METRIC model for estimating evapotranspiration using satellite imagery Discusses principles and algorithms employed by the model Highlights accurate estimation of evapotranspiration T**hrough energy balance and vegetation water stress**
(Senay et al., 2013)	Reviews remote sensing-based models for estimating actual evapotranspiration Provides overview of approaches, algorithms, and data sources Discusses strengths and limitations of different techniques **for selecting appropriate methods**
(Bajgiran et al., 2008)	Assesses AVHRR-based vegetation indices for drought monitoring Correlates satellite-derived NDVI and VCI with precipitation Demonstrates NDVI's effectiveness in reflecting precipitation **Shows potential of remote sensing data in drought monitoring**
(Alahacoon and Edirisinghe, 2022)	Provides comprehensive assessment of drought monitoring indices Categorizes indices into traditional and remote sensing-based Discusses advancements in satellite technology for index development Highlights importance of indices in quantifying drought severity **Emphasizes potential of remote sensing for effective monitoring**
(Farhan and Al-Bakri, 2019)	Discusses remote sensing and geospatial techniques for drought monitoring in Jordan Explores correlations between remote sensing indices and soil moisture measurements Recommends adoption of remote sensing indices for monitoring

These articles collectively provide a comprehensive understanding of remote sensing models and techniques for water stress detection and drought monitoring. They cover various aspects such as estimating evapotranspiration, monitoring vegetation water stress, assessing drought conditions, and utilizing different remote sensing data sources and algorithms. The studies emphasize the potential and significance of remote sensing in accurately quantifying water stress and improving drought monitoring strategies. Researchers and practitioners can benefit from the insights and recommendations presented in these articles when selecting appropriate methods for their specific applications.

APPLICATIONS AND IMPLICATIONS

VPD and CWSI-based sensors have significant practical implications in various aspects of agriculture and water management. Here are key points to consider when discussing the applications and implications of these sensors:

Precision Irrigation Management

- VPD and CWSI-based sensors provide real-time and accurate information on plant water stress, enabling precise irrigation management. Farmers can adjust irrigation schedules based on actual plant needs, optimizing water use efficiency and minimizing water waste.

- By implementing precision irrigation practices guided by VPD and CWSI measurements, farmers can ensure that crops receive the right amount of water at the right time, avoiding over-irrigation or under-irrigation.

- Improved precision irrigation management reduces the risk of yield loss, enhances crop quality, and promotes sustainable water use practices.

Water Conservation

- VPD and CWSI-based sensors play a crucial role in water conservation efforts. By accurately assessing plant water stress, these sensors help avoid unnecessary watering and prevent water wastage.

- Implementing VPD and CWSI-based irrigation strategies allows for targeted watering, focusing irrigation efforts only on plants experiencing water stress. This approach reduces water consumption and conserves valuable water resources.

- Water conservation practices driven by VPD and CWSI-based sensors contribute to environmental sustainability, particularly in regions prone to water scarcity or drought conditions.

Sustainable Agriculture

- The adoption of VPD and CWSI-based sensors supports sustainable agricultural practices. By monitoring plant water stress levels, farmers can optimize water management strategies and reduce the environmental impact associated with excessive water use.

- Precise water stress assessment using VPD and CWSI-based sensors helps maintain optimal crop health, leading to improved crop productivity and resilience to environmental stressors.

- Sustainable water management practices driven by VPD and CWSI-based sensors contribute to the preservation of soil quality, minimize nutrient leaching, and support long-term agricultural sustainability.

Benefits for Stakeholders

- Farmers benefit from improved water management and irrigation efficiency, leading to increased crop yields, reduced production costs, and improved profitability.

- Water resource managers gain valuable insights into plant water stress patterns, enabling them to allocate water resources effectively and make informed decisions regarding water allocation and distribution.

- Policymakers can leverage VPD and CWSI-based sensors to develop evidence-based water management policies and regulations. These sensors provide valuable data for assessing the impact of water stress on agricultural production and guiding sustainable water resource management practices.

In summary, the application of VPD and CWSI-based sensors in precision irrigation management, water conservation, and sustainable agriculture offers significant benefits. These sensors empower farmers, water resource managers, and policymakers with accurate information on plant water stress, leading to improved water use efficiency, enhanced crop productivity, and sustainable water management practices.

CHALLENGES AND FUTURE DIRECTIONS

Despite the advancements in VPD and CWSI-based water stress detection sensors, several challenges and opportunities for improvement exist. When discussing the challenges and future directions, consider the following points:

Sensor Accuracy and Reliability

- One of the primary challenges is ensuring the accuracy and reliability of VPD and CWSI-based sensors across different environmental conditions, crop types, and growth stages. Sensor calibration, maintenance, and validation are crucial for obtaining accurate and consistent measurements.

- Further research is needed to enhance sensor accuracy, reduce measurement errors, and improve the robustness of the sensors in challenging field conditions.

Sensor Applicability and Affordability

- Wide-scale adoption of VPD and CWSI-based sensors can be hindered by their cost and accessibility. Developing cost-effective sensor options and exploring innovative manufacturing techniques can make these sensors more affordable and accessible to a broader range of farmers and stakeholders.

- Standardization of sensor designs and protocols can also facilitate their widespread use and compatibility with existing irrigation systems and technologies.

Data Integration and Decision Support

- Integrating sensor data with decision support systems and irrigation scheduling tools is crucial for effective water management. Ensuring seamless data integration, compatibility, and interoperability between sensors and digital platforms will enable farmers and water managers to make informed decisions based on real-time plant water stress information.

- Developing user-friendly interfaces and decision support tools that can interpret sensor data and provide actionable recommendations is vital for practical implementation and adoption.

Crop-Specific Calibration and Recommendations

- Each crop has unique water requirements and response patterns to water stress. Developing crop-specific calibration methods and establishing optimal threshold values for different crops will improve the accuracy and reliability of VPD and CWSI-based recommendations.

- Further research is needed to refine crop-specific calibration techniques and develop comprehensive guidelines for interpreting sensor data and providing crop-specific irrigation recommendations.

Integration with Other Technologies

- Exploring the integration of VPD and CWSI-based sensors with other emerging technologies, such as remote sensing, machine learning, and internet of things (IoT), can enhance the capabilities and applicability of water stress detection systems.

- Leveraging the synergy between different technologies can provide a more comprehensive understanding of plant water stress dynamics and enable precise and automated irrigation management.

In conclusion, addressing the challenges associated with VPD and CWSI-based water stress detection sensors requires ongoing research and development efforts. By improving accuracy, affordability, data integration, and calibration techniques, these sensors can offer valuable insights for effective water management. Standardization, validation, and integration with decision support systems are essential for maximizing the potential of these sensors in real-world applications.

CONCLUSION

In conclusion, this review has explored the significance of VPD and CWSI-based approaches in water stress detection and their potential for sustainable water resource management in agriculture. The key findings and insights can be summarized as follows:

1. VPD and CWSI-based sensors provide valuable information for assessing and monitoring plant water stress, enabling precise irrigation management and water conservation strategies.

2. The concepts of VPD and CWSI offer effective means to quantify and interpret plant water stress levels.

3. Various sensor technologies, including thermal imaging, infrared thermography, capacitance sensors, and dielectric sensors, have been utilized in the development of CWSI-based sensors.

4. Integration of VPD and CWSI approaches has demonstrated improved accuracy and reliability in water stress assessment, providing a more comprehensive understanding of plant water needs.

5. Advancements in sensor technologies, data analytics, and modeling techniques, along with emerging trends like wireless sensor networks, IoT, and AI, are driving innovation in VPD and CWSI-based sensors.

6. The practical applications of VPD and CWSI-based sensors in precision irrigation management and water conservation have significant implications for farmers, water resource managers, and policymakers.

7. However, challenges related to sensor accuracy, applicability, affordability, data integration, and crop-specific calibration need to be addressed to fully leverage the potential of VPD and CWSI-based sensors.

8. Future directions should focus on standardization, validation, and integration of sensor data with decision support systems, as well as interdisciplinary collaborations to drive advancements in the field.

9. Continued research and development efforts are crucial to overcome challenges, refine sensor technologies, and enhance the accuracy, applicability, and affordability of VPD and CWSI-based sensors.

In conclusion, VPD and CWSI-based approaches offer promising solutions for water stress detection in agriculture. They provide actionable insights to optimize water use efficiency, enhance crop productivity, and promote sustainable water resource management. To fully realize their potential, interdisciplinary collaborations, technological advancements, and ongoing research are necessary. By addressing the existing challenges and fostering innovation, VPD and CWSI-based sensors can play a pivotal role in addressing the global water stress challenge and ensuring a more sustainable future for agriculture.

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