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**Alagesan Arumugam**  
Associate Professor  
(Agronomy), Indian Council of  
Agricultural Research-Krishi  
Vigyan Kendra, Tamil Nadu  
Agricultural University,  
Pudukottai, Tamil Nadu,  
India

**Jesupriya Poornakala Selvaraj**  
Associate Professor (FSN),  
Indian Council of Agricultural  
Research-Krishi Vigyan  
Kendra, Tamil Nadu  
Agricultural University,  
Pudukottai, Tamil Nadu,  
India

**Thukkaiyannan Palaniappan**  
Associate Professor,  
(Agronomy), Indian Council of  
Agricultural Research-Krishi  
Vigyan Kendra, Tamil Nadu  
Agricultural University,  
Tiruppur, Tamil Nadu, India

**Corresponding Author:**  
**Alagesan Arumugam**  
Associate Professor  
(Agronomy), Indian Council of  
Agricultural Research-Krishi  
Vigyan Kendra, Tamil Nadu  
Agricultural University,  
Pudukottai, Tamil Nadu,  
India

## Assessing the water stress of crop plants using infrared thermal imaging

**Alagesan Arumugam, Jesupriya Poornakala Selvaraj and Thukkaiyannan Palaniappan**

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### Abstract

Infrared thermal imaging is a significant advancement in managing crop water stress, offering a non-invasive approach to monitor plant health and irrigation requirements effectively. Research studies emphasize that canopy temperature-derived metrics can serve as early stress indicators, improving water management practices in agriculture. For example, research by Foral *et al.*, (2021) <sup>[13]</sup> showcases the potential of thermal imaging in detecting drought stress in creeping bentgrass before visible symptoms emerge. Additionally, studies by Cegarra E *et al.*, (2021) <sup>[11]</sup> highlight the effectiveness of UAV-based Crop Water Stress Index (CWSI) measurements in monitoring almond trees, advocating for precision agriculture techniques. The integration of thermal imaging technologies is crucial for refining irrigation strategies and ensuring sustainable crop production in water-scarce environments as agricultural practices evolve. The utilization of infrared thermal imaging for assessing crop water stress yields valuable insights into plant irrigation needs. Canopy temperature metrics provide early detection of stress conditions, aiding in optimizing irrigation schedules and enhancing water use efficiency. Advanced sensor technologies like Vapor Pressure Deficit (VPD) and Crop Water Stress Index (CWSI) offer precise data on water stress levels in diverse crops, facilitating efficient resource management. By combining these innovative approaches, the agricultural sector can enhance sustainability practices, optimize resource allocation, and improve resilience against environmental challenges. These findings play a crucial role in refining irrigation methods, boosting crop yields, and promoting informed decision-making in agricultural management.

**Keywords:** Thermal image, infrared, crop water stress index

### 1. Introduction

In the context of modern agriculture, the assessment of crop water stress is increasingly critical due to the escalating demands for food production and the unpredictable patterns of climate change. Understanding the hydration status of crops not only informs irrigation strategies but also aids in maximizing yield and ensuring food security. Traditional methods of measuring water stress often involve labor-intensive practices that can yield inconsistent results. However, infrared thermal imaging has emerged as a revolutionary technology that offers a non-invasive, efficient means of monitoring plant health in real time. By capturing the thermal signatures emitted by crops, this advanced imaging technique allows for the detection of water stress long before visible wilting occurs. Thus, integrating infrared thermal imaging into agricultural practices presents a promising avenue for more precise water management strategies, ultimately leading to enhanced crop resilience and sustainable farming practices.

### 2. Definition of crop water stress

Understanding crop water stress is essential for optimizing agricultural productivity, particularly in regions subject to water scarcity. Crop water stress occurs when the water supply is insufficient to meet the physiological demands of plants, leading to reduced growth, yield, and overall health. Signs of this stress include wilting, leaf discoloration, and decreased photosynthetic activity, which can be detrimental to crop viability. Remote sensing technologies, including infrared thermal imaging, provide valuable tools for assessing this stress by measuring leaf temperature and determining stomatal responses to water availability. Research indicates that indices such as the water deficit index correlate closely with crop physiological parameters, aiding in the identification of water-stressed

plants (Albrizio R *et al.*, 2020) <sup>[1]</sup>. Furthermore, advancements in thermographic techniques allow for detailed mapping of water stress at the field level, enhancing irrigation strategies to ensure adequate water supply and improve agricultural resilience in the face of climate change (Fata L *et al.*, 2021) <sup>[15]</sup>.

### 3. Importance of assessing water stress in agriculture

The assessment of water stress in agriculture has emerged as a critical component for sustainable crop management, particularly in regions facing climate variability. Understanding water stress not only aids in optimizing irrigation practices but also enhances overall crop health and yield. Advanced technologies, such as infrared thermal imaging, enable farmers to monitor plant responses to varying water availability accurately. This precision is vital, especially in arid regions where water scarcity is prevalent, as highlighted by research emphasizing the need for effective water resource utilization to sustain agricultural productivity (Fata L *et al.*, 2021) <sup>[15]</sup>. Additionally, small unmanned aircraft systems (sUAS) have revolutionized the monitoring process by providing high-resolution data necessary to identify stress in crops, thus facilitating timely interventions (Bremer *et al.*, 2023) <sup>[6]</sup>. By utilizing these innovative techniques, agricultural stakeholders can make informed decisions, ultimately leading to improved resource management and resilience against water shortages.

### 4. Overview of infrared thermal imaging technology

Infrared thermal imaging technology has emerged as a critical tool in the assessment of crop water stress, enabling precise monitoring of plant health and irrigation needs. This non-invasive technique measures the thermal radiation emitted by plants, providing valuable insights into transpiration rates and overall physiological states. By detecting variations in surface temperature, thermal imaging helps identify areas of water deficiency before visual symptoms manifest. As highlighted in recent studies, accurate assessment and monitoring of plant water stress are essential for optimizing irrigation strategies and enhancing water-use efficiency (Rezvani F *et al.*, 2023) <sup>[12]</sup>. Moreover, the integration of thermal imaging with other remote sensing technologies can further enrich agricultural practices, expanding the potential for real-time data collection and analysis. Consequently, infrared thermal imaging stands out not only for its immediacy and precision in detecting water stress but also as a significant contributor to sustainable agricultural management practices.

### 5. Principles of Infrared Thermal Imaging

The principles of infrared thermal imaging play a crucial role in assessing crop water stress by providing non-invasive and accurate measurements of plant temperature. This technology operates by detecting the infrared radiation emitted from objects, converting it into visible data that reflect thermal properties without direct contact, which is essential in agricultural settings. Recent advancements have enhanced the effectiveness of thermal imaging in monitoring crop health, as evidenced by its application in evaluating various quality traits of agricultural products. For instance, the integration of small unmanned aircraft systems (sUAS) has revolutionized remote sensing, offering a cost-effective means to monitor crop stress compared to traditional methods (Bremer *et al.*, 2023) <sup>[6]</sup>. Furthermore,

thermal imaging has shown promise in detecting specific indicators of plant stress, such as transpiration rates and soil moisture levels, allowing for timely interventions and improved crop management strategies (Al-Rejaie *et al.*, 2020) <sup>[3]</sup>.

### 5.1. Explanation of infrared radiation and thermal imaging

Infrared radiation plays a critical role in thermal imaging technology, enabling precise assessment of crop water stress. This technique utilizes the infrared spectrum emitted by objects, primarily plants, to derive temperature readings that correlate with physiological conditions. By capturing the thermal emissions, thermal imaging converts this data into temperature distribution maps, facilitating the identification of stress in crops due to water shortages. Research demonstrates that infrared thermography can successfully measure leaf temperatures, which serve as essential indicators for calculating the Crop Water Stress Index (CWSI) (Cukrov A *et al.*, 2021) <sup>[2]</sup>. As water scarcity becomes a growing concern, particularly in arid regions, the application of thermal imaging in agriculture becomes increasingly vital. It not only allows for timely irrigation decisions but also enhances resource management by providing immediate feedback regarding plant health and water requirements (Fata L *et al.*, 2021) <sup>[15]</sup>. Thus, infrared thermal imaging emerges as an indispensable tool in modern agricultural practices.

### 5.2. How thermal imaging detects plant temperature variations

The implementation of infrared thermal imaging serves as a pivotal technique for detecting temperature variations in plants, providing a crucial insight into their water stress levels. As plants experience water deficiency, their physiological response leads to increased leaf temperatures due to reduced transpiration. By employing thermal imaging, researchers can accurately capture these temperature differentials across large areas, an advantage not easily achieved with traditional measurement methods. This allows for the calculation of the Crop Water Stress Index (CWSI), which correlates leaf temperature with water stress indicators such as leaf water potential (LWP) (Cukrov A *et al.*, 2021) <sup>[2]</sup>. Moreover, thermal imaging technology enhances the understanding of plant water status amid the challenges posed by climate change, as it enables efficient, non-destructive monitoring over extensive agricultural landscapes (Fischer B *et al.*, 2024) <sup>[7]</sup>. Ultimately, this technique plays a significant role in optimizing irrigation practices, thereby promoting sustainable agricultural productivity.

### 6. The relationship between plant temperature and water stress

Understanding the relationship between plant temperature and water stress is essential for effective crop management, particularly in the context of climate variability. When plants experience water stress, their physiological processes are disrupted, leading to increased leaf temperatures due to reduced transpiration rates. Infrared thermal imaging emerges as a critical tool for assessing these temperature changes, enabling the non-destructive monitoring of plant health over extensive areas. For example, crop canopy temperature measurements are pivotal in calculating the

Crop Water Stress Index (CWSI), which assists in formulating irrigation strategies tailored to specific crop needs (Giménez Gallego *et al.*, 2021) <sup>[14]</sup>. Moreover, recent advancements in both proximal and remote sensing methods, including low-cost thermal cameras, offer new avenues for continuously monitoring plant water status and facilitating data collection in real-time (Fischer B *et al.*, 2024) <sup>[7]</sup>. Thus, integrating thermal imaging techniques not only enhances our understanding of plant responses to water stress but also contributes significantly to optimizing irrigation practices.

## 7. Applications of Infrared Thermal Imaging in Agriculture

In recent years, the integration of infrared thermal imaging in agriculture has revolutionized how crop water stress is assessed and managed. By providing precise temperature distribution maps through the detection of emitted infrared radiation, this technology enables farmers to monitor the physiological responses of crops to water availability. As climate change exacerbates water shortages, particularly in arid regions, methods such as those discussed in (Fata L *et al.*, 2021) <sup>[15]</sup> become increasingly vital for efficient water resource use. Furthermore, advancements in small unmanned aircraft systems (sUAS) have made it more feasible to collect thermal data across extensive agricultural landscapes, enhancing the ability to predict and manage crop health under stress conditions, as highlighted in (Bremer *et al.*, 2023) <sup>[6]</sup>. Despite its potential, challenges such as variable weather impacts on thermal data accuracy and the complexity of data processing still need to be addressed for optimal deployment in agricultural practices.

### 7.1. Monitoring crop health and water requirements

Effective monitoring of crop health and water requirements is crucial for enhancing agricultural productivity and sustainability. Technologies such as infrared thermal imaging have emerged as powerful tools for assessing crop water stress, allowing for real-time insights into plant physiological responses to varying water regimes. UAVs, equipped with thermal and multispectral cameras, facilitate the timely identification of crop anomalies and stress indicators throughout the growing season, greatly improving water management practices and crop yield potential. Research has demonstrated that indices like the normalized difference vegetation index (NDVI) can be pivotal in evaluating crop health and water needs, with UAV-derived data providing enhanced accuracy in assessing irrigated areas and water productivity (Chimonyo *et al.*, 2020) <sup>[8]</sup>. Moreover, studies indicate that integrating remote sensing with ground-based data can significantly optimize the evaluation of crop conditions and water stress levels, leading to improved agricultural outcomes (Albrizio R *et al.*, 2020) <sup>[1]</sup>.

### 7.2. Early detection of water stress in various crops

The early detection of water stress in crops is crucial for optimizing irrigation practices and ensuring sustainable agricultural productivity. Emerging technologies, particularly infrared thermal imaging, facilitate the monitoring of complex physiological responses to water deficiencies. By capturing the thermal properties of plant foliage, these systems can identify variations in leaf temperature that indicate water stress before visible

symptoms emerge. This capability is further enhanced by innovations in small unmanned aircraft systems (sUAS), which offer affordable yet effective means to survey large agricultural areas quickly and accurately, as discussed in (Bremer *et al.*, 2023) <sup>[6]</sup>. Simultaneously, the integration of remote sensing technologies can support precision agriculture by analyzing spectral reflectance changes related to crop health, thereby allowing farmers to address potential threats from both water stress and pest outbreaks. Such advancements underscore the significance of early intervention strategies in managing crop health and resilience.

### 7.3. Integration with precision agriculture practices

The integration of precision agriculture practices with advanced technologies like infrared thermal imaging is pivotal for enhancing agricultural efficiency and sustainability. By accurately assessing crop water stress, farmers can optimize irrigation strategies, culminating in significant water conservation while maintaining yield. This necessity is underscored by the challenges posed by climate change and diminishing water resources, particularly in arid regions where effective management is crucial (Fata L *et al.*, 2021) <sup>[15]</sup>. Moreover, the implementation of drone technology within these precision practices offers a promising avenue for real-time monitoring and data acquisition, facilitating timely interventions based on crop health assessments (Dawodu *et al.*, 2020) <sup>[9]</sup>. Despite the technological advantages, obstacles such as high equipment costs and the need for refined image analysis techniques remain critical considerations for widespread adoption. Nonetheless, as improvements in technology emerge, the integration of these practices holds the potential to revolutionize resource management in agriculture, leading to enhanced productivity and environmental stewardship.

## 8. Advantages and Limitations of Infrared Thermal Imaging

The application of infrared thermal imaging in assessing crop water stress offers significant advantages while also presenting certain limitations. This non-invasive technique allows for the rapid detection of plant temperature variations, which can correlate with water stress levels, thereby significantly enhancing irrigation management practices. The ability to identify stressed plants across large fields effectively improves water use efficiency, a critical requirement in sustainable agriculture, as emphasized by the insights derived from Crop Water Stress Index (CWSI) analyses (Rezvani F *et al.*, 2023) <sup>[12]</sup>. However, the limitations of infrared thermal imaging cannot be overlooked; factors such as atmospheric conditions, sensor calibration, and the inherent spatial resolution of the imaging systems can affect the accuracy of assessments. Moreover, the reliance on environmental parameters can complicate direct comparisons between different studies, posing challenges for the standardization and validation of results (Baysal-Gurel *et al.*, 2021) <sup>[5]</sup>. Thus, while infrared thermal imaging presents a promising tool for monitoring crop health, its efficacy is contingent upon addressing these limitations.

## 9. Benefits of using thermal imaging for water stress assessment

Thermal imaging has emerged as a transformative tool for

assessing water stress in crops, facilitating more efficient irrigation management and sustainable agricultural practices. By providing a non-invasive means to measure plant temperature, thermal imaging allows for the detection of physiological changes induced by water deficits, which can be correlated with vital traits such as transpiration and photosynthesis. This method surpasses traditional water stress assessment techniques, offering timely insights that enable farmers to make informed decisions regarding irrigation scheduling and crop management. The integration of low-cost thermal cameras, enhanced through advanced image processing techniques like the proposed VisTA-SR method, further democratizes access to this technology, fostering broader application in the field (Bailey *et al.*, 2024) <sup>[4]</sup>. Additionally, the combination of thermal imaging with methodologies such as Vapor Pressure Deficit (VPD) and Crop Water Stress Index (CWSI) presents a robust framework for optimizing water resource management, ultimately contributing to more resilient agricultural systems (Rezvani F *et al.*, 2023) <sup>[12]</sup>.

### 10. Challenges and limitations of the technology

While infrared thermal imaging presents significant advancements in assessing crop water stress, several challenges and limitations impede its widespread application. One primary concern is the accuracy of thermal data acquisition, which can be adversely affected by variable environmental conditions, such as ambient temperature and humidity fluctuations, leading to potential measurement errors. Additionally, the high costs associated with sophisticated thermal imaging equipment and platforms present a barrier to accessibility for many small-scale farmers, resulting in unequal adoption of the technology within the agricultural sector (Rezvani F *et al.*, 2023) <sup>[12]</sup>. Furthermore, the complexities inherent in image analysis and processing necessitate specialized skill sets, often limiting the effective interpretation of thermal data (Rezvani F *et al.*, 2023) <sup>[12]</sup>. These challenges underscore the need for ongoing research and development to refine the technology, improve its accuracy, and enhance usability, ultimately enabling broader implementation for effective water stress management in agriculture.

### 11. Comparison with traditional methods of assessing water stress

Traditional methods of assessing water stress in crops often rely on labor-intensive techniques such as visual inspections, physiological measurements, and the use of soil moisture probes. While these conventional approaches can yield relevant data, they frequently lack the precision and efficiency required for contemporary agricultural practices. In contrast, infrared thermal imaging offers a non-invasive and rapid means of monitoring plant water stress by detecting temperature variations indicative of physiological responses to water deficits. This method aligns with the findings in (Rezvani F *et al.*, 2023) <sup>[12]</sup>, which emphasize the importance of accurate detection for optimizing irrigation strategies. Furthermore, advancements in image-based techniques have also improved frost detection, showcasing automation potential absent in traditional methods (Diepeveen *et al.*, 2022). By integrating these innovative technologies into agricultural practices, we can significantly enhance our ability to manage water resources effectively and promote sustainable crop production in an era of increasing environmental challenges.

## 12. Conclusion

In conclusion, the application of infrared thermal imaging represents a pivotal advancement in the management of crop water stress, providing a non-invasive method for monitoring plant health and irrigation needs. The studies reviewed illustrate that metrics derived from canopy temperatures can serve as early indicators of stress conditions, significantly enhancing water management practices in agriculture. For instance, the research highlighted in underscores the potential of thermal imaging to identify drought stress in creeping bentgrass, suggesting that specific temperature metrics indicate stress before visible symptoms appear. Additionally, the findings reported in (Cegarra E *et al.*, 2021) <sup>[11]</sup> demonstrate the efficacy of UAV-based Crop Water Status Index (CWSI) measurements in monitoring almond trees, reinforcing the need for precision agriculture. Ultimately, as agricultural practices evolve, the integration of thermal imaging technologies will be essential for optimizing irrigation strategies and ensuring sustainable crop production in water-scarce environments.

### 12.1. Summary of key findings

The integration of infrared thermal imaging in assessing crop water stress has yielded significant findings that enhance our understanding of plant irrigation needs. Notably, research indicates that metrics derived from canopy temperature ( $T_c$ ) can serve as early indicators of water stress, effectively identifying conditions prior to visible wilt (Foral *et al.*, 2021) <sup>[13]</sup>. This underscores the potential of consistent monitoring through thermal imaging to optimize irrigation scheduling, ultimately leading to improved water use efficiency. Moreover, advancements in sensor technologies, including Vapor Pressure Deficit (VPD) and Crop Water Stress Index (CWSI), further enrich the field by providing precise data on water stress levels in various crops (Rezvani F *et al.*, 2023) <sup>[12]</sup>. By combining these innovative approaches, the agricultural sector can better manage resources and foster sustainable practices, illuminating a pathway towards resilience in the face of persistent environmental challenges. Such findings are essential for refining irrigation methods and enhancing crop yields through informed management strategies.

### 12.2. Future prospects for infrared thermal imaging in agriculture

The future prospects for infrared thermal imaging in agriculture appear promising, particularly in enhancing the assessment of crop water stress. As precision agriculture continues to evolve, the integration of advanced thermal imaging technologies will enable farmers to monitor crop health more accurately and respond to water deficits promptly. Innovations in sensor technology, such as the interplay between Vapor Pressure Deficit (VPD) and Crop Water Stress Index (CWSI), are crucial in providing insights into plant stress conditions, ultimately optimizing irrigation practices and improving water use efficiency (Rezvani F *et al.*, 2023) <sup>[12]</sup>. Moreover, the adoption of Unmanned Aerial Vehicles (UAVs) equipped with thermal cameras allows for comprehensive monitoring of crops throughout their growth cycle, facilitating timely interventions where necessary (Chimonyo *et al.*, 2020) <sup>[8]</sup>. These advancements will not only bolster agricultural productivity but also contribute to sustainable water resource management, essential in

addressing the challenges posed by climate change and global food security.

### 12.3. Final thoughts on the importance of water stress assessment for sustainable farming

In conclusion, the assessment of water stress in crops is pivotal for the sustainability of agricultural practices in an increasingly resource-constrained world. By employing sophisticated techniques such as infrared thermal imaging, farmers can obtain precise and real-time data on crop water needs, enabling them to make informed irrigation decisions. This proactive approach not only enhances crop yield but also conserves precious water resources, fostering an environmentally sustainable farm management strategy. Furthermore, understanding water stress patterns facilitates the optimization of agricultural productivity while minimizing ecological footprints, thus supporting the long-term viability of farming ecosystems. As climate variability continues to challenge traditional farming methods, it becomes increasingly evident that robust water stress assessment is not merely an option but a necessity for ensuring food security and resilience in agriculture. Ultimately, integrating advanced technologies with sustainable practices can lead to a more efficient and responsible agricultural framework.

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