**The Role of CCATD and CTD in Assessing Crop Water Status and Stress Response in High-Tech Agriculture: A Comprehensive Review**

**ABSTRACT**

Crop temperature regulation is a fundamental aspect of plant physiology, particularly under fluctuating environmental conditions. Temperature-based indices, such as Crop Canopy Air Temperature Difference (CCATD) and Canopy Temperature Depression (CTD), serve as crucial indicators of plant water status, transpiration efficiency, and drought response. CCATD, defined as the difference between canopy temperature (Tc) and air temperature (Ta), provides insights into water stress, where higher values signify limited transpiration and increased heat accumulation. Conversely, CTD, calculated as the difference between Ta and Tc, reflects the plant's cooling capacity, with higher values indicating active transpiration and efficient water use. The inverse relationship between these indices enhances their applicability in crop monitoring, precision irrigation, and plant breeding programs for stress-resilient genotypes. Advanced technologies, including infrared thermometry, UAV-mounted thermal imaging, and satellite-based remote sensing, facilitate accurate CCATD and CTD assessments at various scales. Environmental variables such as solar radiation, vapor pressure deficit (VPD), wind speed, and soil moisture dynamics significantly influence these indices, necessitating their integration with multi-spectral and physiological parameters for improved stress detection. This study underscores the pivotal role of CCATD and CTD in optimizing agricultural water management, identifying climate-resilient cultivars, and advancing precision agriculture. Future research should focus on integrating AI-driven analytics and high-throughput phenotyping to enhance the predictive accuracy of these indices, ensuring sustainable crop production under increasing climate variability.

**Keywords**: Crop Canopy Air Temperature Difference (CCATD), Canopy Temperature Depression (CTD), Plant Water Status, Crop Stress Monitoring, Precision Agriculture

**INTRODUCTION**

Crop temperature regulation is a fundamental aspect of plant physiology, influencing a range of biochemical, developmental, and physiological processes **(Jones, 1999)**. As a critical environmental factor, temperature determines plant metabolic rates, photosynthetic efficiency, water use and stress tolerance **(Taiz and Zeiger, 2010).** With global temperatures rising and extreme weather events becoming more frequent, understanding plant responses to heat and water stress is essential for sustainable crop production **(IPCC, 2021).** Temperature-based indices, such as Crop Canopy Air Temperature Difference (CCATD) and Canopy Temperature Depression (CTD), have emerged as key indicators for assessing plant water status, transpiration efficiency, and drought stress response **(Jackson *et al.,* 1981).** These indices provide valuable insights into plant-environment interactions and have broad applications in plant breeding, crop physiology, and precision agriculture **(Zia *et al.,* 2013; Jones *et al.,* 2018).**

**Understanding Canopy Temperature-Based Indices**

**1. Crop Canopy Air Temperature Difference (CCATD):** CCATD is the temperature difference between the crop canopy temperature (Tc) and the air temperature (Ta) **(Keener and Kircher, 1983; Duffková, 2006.)**. It serves as an essential parameter for monitoring plant water relations and stress levels **(Jackson *et al.,* 1981).** Under optimal conditions, well-watered plants maintain a lower canopy temperature due to active transpiration, which facilitates evaporative cooling **(Jones, 1999).** However, under water deficit conditions, stomatal closure reduces transpiration, causing an increase in canopy temperature relative to the air temperature. This makes CCATD a reliable metric for detecting early signs of drought stress. Additionally, CCATD is directly influenced by crop temperature regulation mechanisms, as factors such as transpiration cooling, stomatal conductance, and canopy structure determine how effectively a plant maintains its temperature in response to environmental fluctuations **(Zia *et al.,* 2013).** It is mathematically expressed as:

CCATD= Tc ​− Ta

**2. Canopy Temperature Depression (CTD):** CTD refers to the difference between air temperature (Ta) and canopy temperature (Tc) **(Blum *et al.,* 1982; Balota *et al.,* 2008).** It is commonly used to evaluate genotypic variations in drought tolerance, as plants with higher CTD values exhibit better cooling efficiency and, consequently, greater drought resistance **(Amani *et al.,* 1996).** This index is widely applied in breeding programs to select heat- and drought-tolerant cultivars, particularly in crops such as wheat, maize, and rice **(Reynolds *et al.,* 1994).** Higher CTD values are associated with improved transpiration efficiency and water use, making it an essential tool for optimizing irrigation management **(Jones *et al.,* 2018).** The ability of a plant to regulate its canopy temperature through evaporative cooling directly impacts CTD values, highlighting the intricate relationship between crop temperature

regulation and water stress adaptation **(Cossani and Reynolds, 2012).** It is mathematically expressed as:

CTD=Ta−Tc

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| --- | --- | --- |
| **Aspect/ Parameter** | **Crop Canopy Air Temperature Difference (CCATD)** | **Canopy Temperature Depression (CTD)** |
| Definition | The temperature difference between the crop canopy temperature (Tc) and the air temperature (Ta). | The difference between air temperature (Ta) and canopy temperature (Tc). |
| Formula | CCATD= Tc ​− Ta | CTD=Ta−Tc |
| Interpretation | Higher CCATD indicates higher canopy temperature than air, often due to water stress. | Higher CTD indicates a cooler canopy, signifying efficient transpiration and better water status. |
| Relationship | Inversely related to CTD; a higher CCATD often corresponds to a lower CTD. | Inversely related to CCATD; a higher CTD often corresponds to a lower CCATD. |
| Physiological Implication | Reflects plant water status and transpiration efficiency. | Indicates genotypic variations in drought tolerance and evaporative cooling. |
| Role in Stress Detection | Positive CCATD suggests drought stress due to reduced transpiration. | Higher CTD values suggest better heat and drought tolerance in crops. |
| Commonly Used in | To assess early plant water stress detection, evapotranspiration efficiency, and crop health | Serves as an indicator of plant transpiration efficiency and frequently used in breeding programs to select heat- and drought-tolerant varieties. |
| Application Fields | Precision agriculture, remote sensing and irrigation management. | Plant breeding, crop physiology, and drought tolerance screening. |

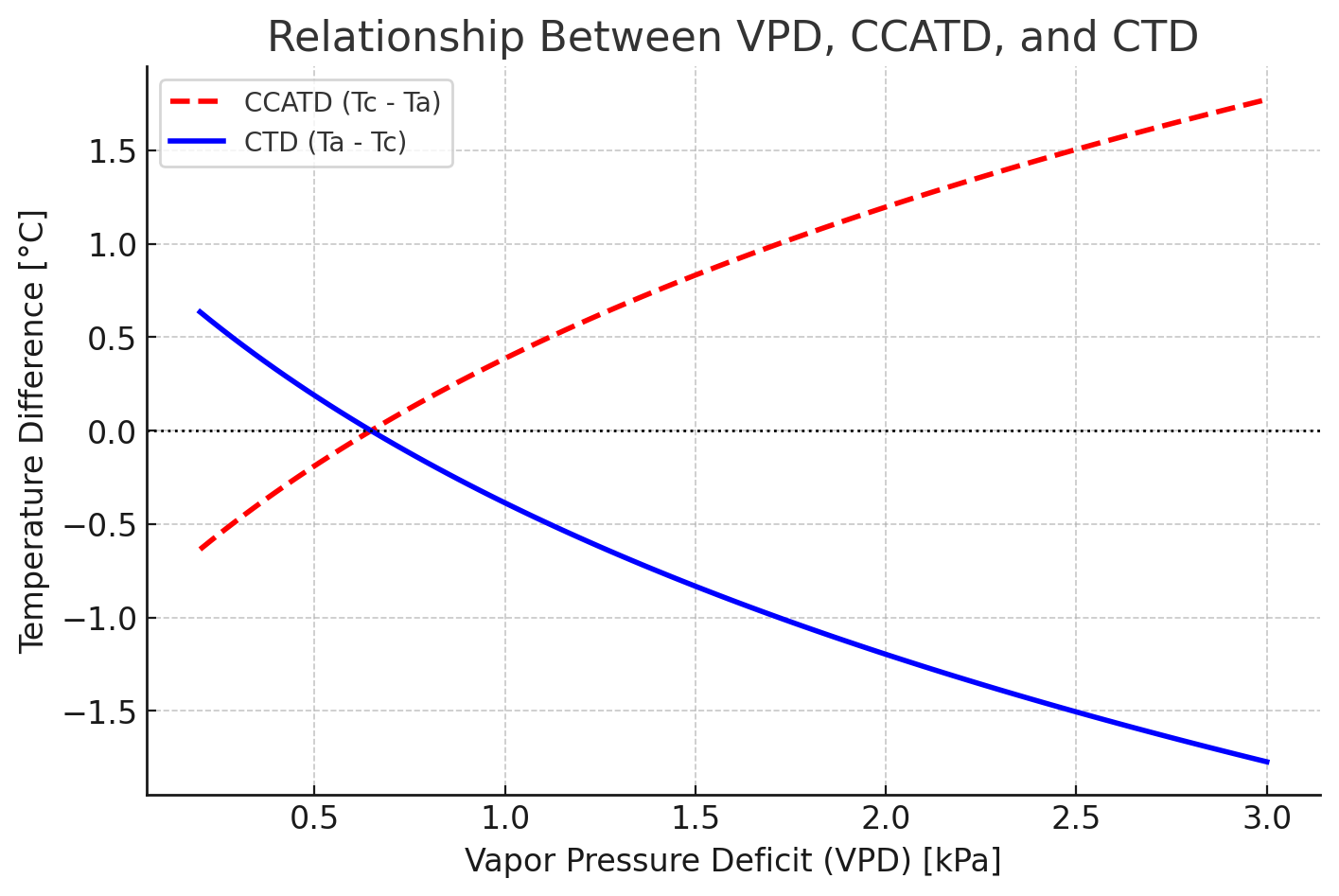
**Table 1: Overview of Crop Canopy Air Temperature Difference (CCATD) and Canopy Temperature Depression (CTD)**

A positive CTD indicates efficient transpiration, where the canopy remains cooler than ambient air due to active water loss through stomata. In contrast, a low or negative CTD reflects water stress, as restricted transpiration leads to a higher canopy temperature **(Zia *et al.,* 2013).**CTD is particularly valuable in plant breeding programs for selecting drought- and heat-tolerant genotypes, as well as in remote sensing and agronomic management for assessing crop performance under stress conditions **(Reynolds *et al.,* 1997).** Both Tc and Ta should be measured in the same temperature unit (e.g., degrees Celsius) to get a meaningful difference for CCATD and CTD.

**Relationship between Crop Canopy Air Temperature Difference (CCATD) and Canopy Temperature Depression (CTD)**

Crop Canopy Air Temperature Difference (CCATD) and Canopy Temperature Depression (CTD) are inversely related to each other. Both terms describe the temperature variation between the crop canopy and the surrounding air but from different perspectives **(Jones, 1999; Zia *et al.,* 2013; Fukai and Mitchell, 2022).** Mathematically, this relationship is expressed as:

CTD=−CCATD

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**Figure 1: Relationship between VPD, CCATD, and CTD.** At low VPD → Transpiration is high, canopy stays cool (low CCATD, high CTD); At moderate VPD → Transpiration is balanced, temperature difference is minimal (CCATD and CTD near zero); At high VPD → Stomata close to conserve water, reducing cooling, making the canopy hotter (high CCATD, low CTD).

This inverse relationship means that when CCATD is positive (canopy is hotter than air), CTD is negative, indicating water stress due to limited transpiration and stomatal closure **(Jackson *et al.,* 1981).** Conversely, when CTD is positive (canopy is cooler than air), CCATD is negative, signifying active transpiration and sufficient water availability **(Reynolds *et al.,* 1997).** The integration of CCATD and CTD into crop monitoring systems enables improved stress detection, precise irrigation scheduling, and adaptive management strategies to mitigate the impacts of climate variability on agricultural productivity **(Jones *et al.,* 2018; Amani *et al.,* 1996).**

**CCATD and CTD as Tools for Monitoring VPD Effects on Plant Water Status and Temperature Regulation**

Vapor Pressure Deficit (VPD) is a key environmental parameter representing the difference between the actual moisture content in the air and the maximum amount of moisture the air can hold at a given temperature **(Monteith and Unsworth, 2013).** It is a measure of the atmospheric demand for water and plays a crucial role in plant transpiration, stomatal regulation, and overall plant physiological responses **(Jones, 1992).** By integrating Crop Canopy Air Temperature Difference (CCATD) and Canopy Temperature Depression (CTD) measurements with VPD monitoring, farmers and researchers can enhance irrigation management, breeding for stress-tolerant crops, and climate adaptation strategies in agriculture. These indices provide real-time insights into how plants respond to atmospheric moisture demand under varying environmental conditions **(Blum, 2010; Hatfield *et al.,* 2011).**

**High VPD (Dry Air, High Evaporative Demand):** When VPD is high, the atmosphere exerts a strong evaporative demand on plants. If soil moisture is adequate, plants maintain high transpiration rates, leading to a low CCATD (canopy remains cool) and a high CTD (air is warmer than the canopy) due to efficient evaporative cooling **(Lobell *et al.,* 2014).** However, under water-limited conditions, plants regulate water loss by partially or fully closing their stomata, reducing transpiration. This leads to high CCATD (canopy heats up due to reduced cooling) and low or negative CTD (canopy becomes warmer than air), which are key indicators of drought stress **(Sinclair *et al.,* 2010; Sofi** ***et al.,* 2019).**

**Table 2: Relationship between Vapor Pressure Deficit (VPD), Crop Canopy Air Temperature Difference (CCATD), and Canopy Temperature Depression (CTD) along with their corresponding physiological responses**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Condition** | **VPD (kPa)** | **CCATD** | **CTD** | **Physiological Response** | **Reference** |
| High humidity, low VPD | < 0.5 | Low (near zero or negative) | High (positive) | Stomata remain open, low transpiration, high disease risk. | **Grossiord** ***et al.,* 2020** |
| Optimal VPD | 0.5–1.5 | Negative (canopy cooler than air) | Positive (air warmer than canopy) | Efficient transpiration, active cooling, optimal growth. | **Medina *et al.,* 2019** |
| Moderate drought, increasing VPD | 1.5–2.5 | Positive (canopy slightly warmer than air) | Negative (canopy warmer than air) | Partial stomatal closure, reduced photosynthesis, early water stress. | **Merilo** ***et al.,* 2018** |
| Severe drought, very high VPD | > 2.5 | Highly positive (canopy much warmer than air) | Highly negative (air cooler than canopy) | Stomatal closure, reduced transpiration, severe drought stress. | **Grossiord** ***et al.,* 2020** |

**Low VPD (Humid Air, Low Evaporative Demand):** Under low VPD conditions, the atmospheric demand for water is minimal, resulting in reduced transpiration rates. Consequently, CCATD values are close to zero or slightly negative (canopy temperature is near or slightly below air temperature), and CTD remains high (canopy remains cooler than air) **(Chaves *et al.,* 2003).** However, excessively low VPD can lead to limited stomatal opening, decreased transpiration efficiency, and an increased risk of fungal diseases due to prolonged leaf wetness **(Fanourakis *et al.,* 2020).**

**Instruments for Measuring CCATD and CTD**

#### Accurate measurement of Crop Canopy Air Temperature Difference (CCATD) and Canopy Temperature Depression (CTD) requires specialized instruments capable of detecting both canopy temperature and ambient air temperature under field conditions. These instruments range from handheld sensors to advanced remote sensing technologies integrated with satellites and UAVs (unmanned aerial vehicles) (Jones, 1999; Costa *et al.,* 2013).

#### 1. Infrared Thermometers (IRTs)

#### Infrared thermometers (IRTs) are widely used for point-based measurement of canopy temperature. These devices detect thermal radiation emitted by plant surfaces and convert it into temperature readings. To measure CCATD or CTD, an IRT is aimed at the crop canopy, while a separate sensor records ambient air temperature (Jackson *et al.,* 1981).

#### 2. Infrared Thermal Cameras

#### Infrared (IR) thermal cameras provide a spatially detailed thermal map of crop fields by capturing thermal radiation across a large area. These cameras can be mounted on tripods, UAVs, or manned aircraft for high-resolution temperature mapping (Gonzalez-Dugo *et al.,* 2012).

#### 3. Canopy Temperature Sensors (Fixed and Wireless Systems)

#### Fixed canopy temperature sensors are placed within the field to continuously record temperature variations over time. Wireless sensor networks (WSNs) integrate multiple temperature sensors, transmitting real-time data for continuous monitoring. These systems provide an automated approach for detecting plant water stress and optimizing irrigation (Kim *et al.,* 2011).

#### 4. UAVs (Drones) with Thermal Sensors

#### Unmanned aerial vehicles (UAVs), or drones, equipped with thermal imaging sensors enable rapid and precise measurement of canopy temperature over large agricultural fields. These systems integrate GPS and AI algorithms to analyze crop temperature variations, providing high-resolution thermal imagery (Berni *et al.,* 2009; Ludovis *et al.,* 2017).

#### 5. Satellite-Based Thermal Remote Sensing

#### Satellites such as Landsat-8 (TIRS), MODIS (Terra/Aqua), and Sentinel-3 (SLSTR) provide global-scale thermal imaging for canopy temperature analysis. Satellite-based thermal data allow for long-term monitoring of temperature trends, drought impact, and vegetation health (Meron *et al.,* 2013; Neinavaz *et al.,* 2021).

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| --- | --- |
| Infrared (IR) Thermometers / Plant Stress Monitors - Crop, Soil and Water  Testing | DSC_0258_0.JPG |
| **Infrared Thermometers** | Infrared Thermal Cameras |
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| **Canopy Temperature Sensors** | **UAVs (Drones) with Thermal Sensors** |
| Thermal Infrared Remote Sensing - an overview | ScienceDirect Topics | Weather Station with Multiple Sensors |
| **Satellite-Based Thermal Remote Sensing** | **Weather Stations with Air Temperature Sensors** |

**Figure 2: Instruments for Measuring Crop Canopy Air Temperature Difference (CCATD) and Canopy Temperature Depression (CTD)**

#### 6. Weather Stations with Air Temperature Sensors

For CCATD and CTD calculations, accurate air temperature (Ta) is essential. Automated weather stations (AWS) equipped with high-precision air temperature sensors provide real-time data on ambient conditions. These stations are often used alongside IRTs, UAVs, and satellite measurements to enhance temperature-based stress monitoring **(Anderson *et al.,* 1997).**

**Factors Affecting Crop Canopy Air Temperature Difference (CCATD) and Canopy Temperature Depression (CTD)**

Several environmental, physiological, and agronomic factors influence CCATD and CTD, affecting their accuracy and reliability as indicators of plant water status and stress responses. Understanding these factors is essential for interpreting crop temperature variations and optimizing water management, breeding strategies, and precision agriculture applications.

#### Environmental Factors

* **Ambient Air Temperature:**  Air temperature significantly affects both CCATD and CTD. When air temperature rises, CCATD tends to increase, especially under water stress conditions where transpiration is restricted.
* **Solar Radiation:** Solar radiation also affects canopy temperature; under high radiation, CCATD increases if transpiration is insufficient, whereas a well-watered plant may exhibit a high CTD due to effective cooling through transpiration.
* **Relative Humidity (RH) and Vapor Pressure Deficit (VPD):** These factors directly influence the evaporative demand of the atmosphere. When RH is low and VPD is high, transpiration increases if soil moisture is available, resulting in a lower CCATD and higher CTD. However, under drought conditions, high VPD can cause stomatal closure, leading to increased CCATD and reduced CTD.
* **Wind Speed:** It further affects canopy temperature by promoting heat dissipation; stronger winds generally reduce CCATD and increase CTD by enhancing transpiration.
* **Soil Moisture Availability:** It is another critical factor, as plants experiencing drought have reduced transpiration rates, which leads to a higher CCATD and a lower CTD.

**Table 3: Instruments for Measuring Crop Canopy Air Temperature Difference (CCATD) and Canopy Temperature Depression (CTD) their Advantages and Limitations**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Instrument** | **Description** | **Application** | **Advantages** | **Limitations** | **Reference** |
| Infrared Thermometer (IRT) | Handheld device measuring thermal radiation from the canopy | Point-based measurements in small-scale studies | Quick, portable, and easy to use | Affected by operator handling and sun angle | **Jackson *et al.,* 1981** |
| Infrared Thermal Camera | Captures thermal images of the crop canopy | Large-scale temperature mapping | Provides spatial distribution of canopy temperature | Requires calibration and post-processing | **Jones, 2004** |
| Canopy Temperature Sensors (Fixed/Wireless) | Fixed or wireless sensors placed in the field for continuous monitoring | Automated irrigation and stress monitoring | Provides real-time data, minimizes human error | Installation and maintenance costs | **Gutiérrez *et al.,* 2013; Ortiz *et al.,* 2018** |
| UAVs (Drones) with Thermal Sensors | Drones equipped with thermal imaging cameras | Precision agriculture, drought stress assessment | High-resolution, large-area coverage | Expensive, requires expertise for data analysis | **Ludovis *et al.,* 2017; Impollonia *et al.,* 2022** |
| Satellite-Based Thermal Remote Sensing | Thermal imaging from satellites like Landsat-8, MODIS | Regional/global-scale drought and stress monitoring | Covers vast areas, useful for long-term trends | Lower spatial resolution, affected by cloud cover | **Neinavaz *et al.,* 2021** |
| Weather Stations (Air Temperature Sensors) | Provides real-time air temperature data | Essential for CCATD and CTD calculations | Continuous monitoring of ambient conditions | May not capture localized canopy microclimate | **Jackson *et al.,* 1981** |

#### Physiological Factors

* **Stomatal Conductance:** The ability of plants to regulate transpiration through stomatal conductance significantly influences CCATD and CTD. When stomata close due to drought stress, transpiration decreases, leading to an increase in CCATD and a reduction in CTD.
* **Leaf Area Index (LAI):** LAI affects canopy temperature; a higher LAI increases shading, which helps reduce CCATD and enhances CTD by maintaining a cooler canopy.
* **Crop Growth Stage:** The stage of crop development also determines transpiration efficiency and temperature regulation. Young plants with limited foliage tend to have higher CCATD due to lower transpiration rates, while mature crops with a fully developed canopy exhibit higher CTD due to their increased ability to regulate temperature through transpiration.
* **Genotypic Variability:** Drought-sensitive cultivars often exhibit higher CCATD due to poor transpiration control, whereas drought-tolerant genotypes maintain a higher CTD under stress conditions by sustaining transpiration and cooling mechanisms.

#### Agronomic and Management Factors

* **Irrigation Practices:** Irrigation directly influences CCATD and CTD. Insufficient irrigation leads to water stress, increasing CCATD, whereas well-irrigated crops maintain transpiration and cooling, resulting in higher CTD.
* **Fertilization:** Nutrient availability affects plant vigor and stomatal function. Nutrient deficiencies can impair transpiration, leading to increased CCATD, while adequate nutrient supply enhances transpiration efficiency, promoting a higher CTD.
* **Mulching:** By conserving soil moisture, mulching helps regulate canopy temperature, reducing CCATD and increasing CTD by sustaining transpiration.
* **Plant Density:** Higher plant density influences the canopy microclimate by increasing shading, which lowers CCATD and enhances CTD by creating a cooler and more humid environment.

**Harnessing CCATD and CTD for Climate-Resilient Agriculture**

Climate change poses significant threats to global food security by increasing the frequency of droughts, heatwaves, and unpredictable weather patterns. Crop Canopy Air Temperature Difference (CCATD) and Canopy Temperature Depression (CTD) are essential physiological indicators that aid in monitoring and mitigating these impacts on crop production. Their applications in drought adaptation, heat stress management,water-use efficiency, and precision agriculture make them valuable tools for climate-smart farming.

**1. Enhancing Drought Resilience**

**Early stress detection:** CCATD identifies water stress before visible symptoms appear, enabling timely interventions such as irrigation adjustments.

**Selection of drought-tolerant crops:** CTD helps in identifying genotypes with efficient transpiration under heat and drought stress, supporting the development of climate-resilient crop varieties.

**Precision irrigation management:** Integrating CCATD and CTD with soil moisture sensors and remote sensing data optimizes water use, promoting sustainable agricultural practices in water-scarce regions.

**2. Heat Stress Management**

**Monitoring heat stress effects:** A high CCATD (warmer canopy than air) indicates poor transpiration and heat stress, pinpointing vulnerable crops.

**Genotypic screening for heat tolerance:** CTD facilitates the selection of cultivars that maintain canopy cooling under high temperatures, ensuring yield stability despite climate variability.

**Microclimate modification strategies:** CCATD and CTD data support agroforestry, mulching, and shade net applications to mitigate heat stress and improve crop resilience.

**3. Sustainable Water and Resource Management**

**Reducing water wastage:** CCATD-guided irrigation ensures water is applied only when necessary, conserving groundwater and freshwater resources.

**Improving evapotranspiration models:** CCATD and CTD enhance evapotranspiration modeling, aiding regional water resource planning.

**Precision nutrient management:** Variations in CCATD can indicate nutrient deficiencies, enabling targeted fertilization to maintain soil health while minimizing excessive fertilizer use.

**4. Integration with Climate-Smart Technologies**

**Remote sensing and AI-driven climate prediction:** Drones and satellites equipped with thermal sensors analyze CCATD and CTD trends to predict drought and heat stress risks.

**Machine learning for climate adaptation:** AI models process CCATD and CTD data alongside climate forecasts to optimize irrigation, nutrient application, and stress management.

**IoT-enabled precision farming:** Real-time CCATD and CTD monitoring through wireless sensor networks facilitates automated climate adaptation responses.

**5. Yield Prediction and Carbon Footprint Reduction**

**Yield prediction:** Canopy temperature variations provide insights into crop yield potential, helping farmers and researchers optimize agronomic strategies.

**Minimizing excessive irrigation and fertilizer use:** CCATD- and CTD-based precision agriculture reduces unnecessary resource consumption, lowering greenhouse gas emissions.

**Optimizing crop selection and land use:** Data-driven selection of drought-tolerant varieties and optimized planting schedules enhance sustainable land use and productivity.

**DISCUSSION**

CCATD and CTD are valuable indicators for assessing plant water status, transpiration efficiency, and stress adaptation in response to environmental changes. CCATD measures the temperature difference between the crop canopy and the surrounding air, serving as an early indicator of water stress. A high CCATD value suggests reduced transpiration due to stomatal closure, commonly triggered by drought. This makes CCATD particularly useful in remote sensing applications, where thermal imaging and satellite-based monitoring enable large-scale crop stress assessment. However, its accuracy can be influenced by environmental factors such as solar radiation, wind speed, and atmospheric humidity. To improve precision, integrating CCATD with complementary indices like Vapor Pressure Deficit (VPD) and the Normalized Difference Vegetation Index (NDVI) is essential. CTD, in contrast, is widely applied in breeding programs to identify heat- and drought-tolerant cultivars. A high CTD value indicates efficient transpiration and effective stomatal regulation, leading to a cooler canopy temperature. This trait is crucial for selecting genotypes with superior osmotic adjustment and root efficiency under water-limited conditions. Correlations between CTD and yield stability in staple crops, such as wheat and maize, further reinforce its importance in breeding climate-resilient varieties. Although CCATD and CTD are mathematically inverse, their combined use provides comprehensive insights into plant responses to environmental stress. CCATD is particularly relevant for real-time stress detection and irrigation optimization, whereas CTD plays a crucial role in long-term breeding strategies. The integration of both indices with remote sensing technologies, thermal infrared imaging, and AI-driven models can significantly enhance drought monitoring and adaptive agronomic practices. Future research should focus on refining these indices for different crop species and climatic conditions, enhancing their integration with advanced remote sensing and AI-based predictive models. Such advancements will improve drought assessment accuracy, optimize water management strategies, and contribute to climate-resilient agricultural systems.

**CONCLUSION**

CCATD and CTD serve as powerful physiological indicators of plant water status and thermal regulation, offering crucial applications in precision agriculture and plant breeding. CCATD is particularly useful for real-time stress assessment and irrigation optimization, while CTD is instrumental in selecting drought-tolerant cultivars. Their combined application provides a holistic understanding of plant-water interactions, improving decision-making in agriculture. Future advancements should prioritize integrating CCATD and CTD with AI-driven modelling, remote sensing, and physiological trait analysis to enhance drought prediction and water management. Field validation across diverse crop species and climatic zones will further refine these indices, ensuring their effectiveness in precision agriculture. As climate change continues to challenge global food security, leveraging these temperature-based indicators will be essential for developing sustainable, climate-resilient farming systems.

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