Review Article

Advances in Leaf and Canopy Temperature Sensors for Precision Irrigation: A Review

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Abstract
Precision technologies are crucial for sustainable water management, as water scarcity and ineffective irrigation techniques continue to pose significant challenges in agriculture. One of the bases of plant-based irrigation scheduling is plant canopy temperature, which has become a reliable indicator of crop water status. The primary sensor technologies used to measure the temperature of leaves and canopies are discussed in this review, including integrated circuit sensors, thermistors, thermocouples, infrared thermometers, and infrared thermal imaging systems. Thermistors and thermocouples provide precise and affordable point-based measurements, but their scalability and installation are limited. For real-time canopy monitoring, infrared thermometers and thermal imaging provide non-contact options. Despite their higher price, thermal cameras enable the analysis of spatial variability. Low-cost irrigation system automation is made feasible by integrated circuit (IC) sensors, like the LM35, which combine accuracy and affordability. Research confirms that under deficit irrigation strategies, canopy temperature-based indices, notably the Crop Water Stress Index (CWSI), improve water use efficiency and enhance yield responses. However, sensor calibration, environmental variability, and the balance between accuracy and cost continue to be ongoing challenges.

Keywords: Crop Water Stress Index (CWSI), Irrigation scheduling, Plant canopy temperature, Precision agriculture, Sensor technologies

1 Introduction

Agriculture has traditionally been the backbone of the economy; it is the world's primary user of water. Approximately 60% of the world's freshwater supply, sourced from rivers, lakes, reservoirs, and wells, is allocated for irrigation [1]. This system is equally vital in irrigating crops, as the availability of optimum water is necessary to achieve high yields and promote growth and development. However, water conservation has become a serious issue. Traditional irrigation practices often result in excessive watering and increase the likelihood of groundwater pollution when fertilizers and pesticides leach into the groundwater from crop zones, ultimately leading to the depletion of freshwater resources [2].

Precision agriculture offers numerous benefits for sustainable growth, increased yield and profit, improved quality, environmental friendliness, and profitability [3]. In precision irrigation, water management is crucial for elevating crop yield, minimizing costs, and integrating environmental sustainability [4]. Improving irrigation thus conserves water, enhances distribution efficiency, and reduces operational and labor costs, facilitating sustainable practices in agriculture and enabling a better life for farmers.

The utilization of Internet of Things (IoT) and wireless sensor networks as modern technologies in agriculture presents compelling opportunities for a gradual shift toward more sustainable farming practices. Wireless systems significantly enhance crop productivity while being more efficient for water conservation management in irrigation systems [5], [6]. The primary advantage of IoT systems in irrigation is to minimize water consumption [7]. Irrigation scheduling involves determining the amount of water needed and when to apply it to ensure effective water use efficiency (WUE). Applying water beyond the optimum level for plant absorption has been shown to reduce irrigation water use efficiency [8].

Soil moisture sensors and plant-based methods can work very efficiently for irrigation scheduling. Several methods are available for measuring plant water status and canopy temperature. Canopy temperature plays a significant role in determining the crop water stress index and in the threshold temperature–time method for irrigation scheduling [8], [9]. Various technologies have been developed to measure plant canopy temperature, including thermal resistance sensors, thermocouples, and infrared thermal imaging. Among these, infrared thermal imaging is the most commonly used sensing technique in research studies.

Further considerations show that the canopy of the vegetation is a significant factor in photosynthesis, transpiration, and energy exchange and canopy temperature is a critical indicator of the water situation of plants and stress in crops. The measurement of such true values is hard due to humidity, sun radiation and speed of wind, canopy structure and architecture that cause variation in measurement [10]. Recent sensor technologies, in particular, multispectral sensors, and thermal sensors, are becoming more accurate in canopy temperature measurements (spatial temperature mapping and complementing the Internet of Things (IoT) and Wireless Sensor Networks (WSNs) to monitor the temperature of the canopy in real-time) [11], [12]. The innovations enable adaptive irrigation planning and predictive analytics to optimize water utilization to favor large-scale and smallholder farm systems to achieve climate variability and water resource sustainability [13].

This review particularly stands out among earlier literature as it focuses on comparative analysis of leaf and canopy temperature sensors as applied to precision irrigation scheduling and not broadly to sensor applications. It compares the performance of the leading sensing technologies, accuracy, and cost-benefit trade-offs of major sensing technologies, such as thermistors, thermocouples, infrared thermometers, infrared thermal imaging, and integrated circuit (IC) sensors.

Moreover, the paper is innovative since the synthesis of the research recently published allows evaluating the effectiveness of new technologies in overcoming the previous disadvantages associated with cost and scalability and field applicability. This study combines analytical views about pragmatically working devices as opposed to earlier reviews, which mostly generalized the device performances, and provides implications of strategies to manage irrigation sustainably, through integration of a sensor with IoT and wireless networks.

Therefore, the focus of this review is clearly based on the practical uses of temperature sensing technologies in irrigation scheduling and water stress monitoring in an attempt to address the most viable solutions to the commercial and smallholder farming systems. The evaluation and assessment of the methods will be based on the available literature and studies.

2 Irrigation

Irrigation systems employed at the farm level can be categorized into 3 primary categories: sprinkler, surface, and drip systems. Water is distributed as sprays through overhead sprinklers in sprinkler systems. The use of sprinkler irrigation in both small and large scale agricultural systems is being adopted because of its ability to provide equal distribution of water, particularly in areas whose soils are uneven. The new sprinkler systems, such as the center-pivot and side-moving ones, allow precise control of the water distribution and can be easily installed onto the automated controllers that allow climate responsive irrigation. Studies have indicated that sprinkler irrigation can achieve application efficiencies of up to 80–90% under well-managed conditions, and it also reduces soil erosion compared to surface irrigation. However, sprinkler irrigation relies on a pressure-based water supply, which is energy-intensive, and water losses due to wind drift and evaporation remain significant limitations, particularly in dry or windy regions. Recent innovations in IoT-based and variable-rate sprinkler systems are addressing these inefficiencies by enabling dynamic irrigation scheduling based on real-time environmental data [14], [15]. Drip irrigation systems commonly deliver water in small quantities through small tubes with nozzles either above or below the ground. The most popular system for irrigating row crops worldwide is furrow irrigation [16].

Irrigation systems and field application methods play a crucial role in crop cultivation. To address productivity losses associated with water stress from under-irrigation, farmers frequently engage in excessive watering (over-irrigation). This practice negatively impacts productivity, as it wastes water and energy [4]. Knowing the duration, where, and quantity of irrigation is crucial for minimizing crop yield loss due to water stress. The best way to optimize yield response to varied management strategies is to consider both yield per unit of water utilized and maximum profitability for farmers. Four major parameters apply to the requirements of irrigation mentioned below: (1) water available in the soil, (2) water requirement for the crop, (3) amount of precipitation received, and (4) efficiency of the irrigation system [17]. Soil moisture, plant temperature, and evapotranspiration measurements are the most common ways of obtaining these values.

Surface irrigation, on the other hand, remains among the simplest and most prevalent methods of irrigation in the global context, particularly in developing nations, since it is fundamental and demands little operational costs [18]. The water in this method circulates through the superficial movement of water by gravity on the soil to irrigate the root zone. Surface irrigation has cost advantageous nature, however, it is a low water use efficiency (WUE) method due to percolation and surface runoff losses, especially in lumpy topography [19]. Laser land leveling, gated pipes, and controlled inflow systems are used to achieve modernization, as underscored in the recent. Studies have a long way in helping to enhance the uniformity of distribution and reduce water wastage. Adaptation of sensor-based control systems of surface irrigation can also maximize the period of inflow with respect to the soil moisture as a feedback mechanism.

As can be seen in Table 1, the comparative summary of irrigation systems is provided. Each system presents particular advantages in water management and adaptability to various field conditions. However, the efficiency, operating cost, and maintenance should be considered when choosing the most suitable systems.

Table 1: Comparative summary of irrigation systems.

System	Description	Advantage	Disadvantage	Ref.
Sprinkler Irrigation	Water is distributed through overhead nozzles simulating rainfall.	Uniform water distribution; adaptable to various soil types; suitable for undulating terrain.	High energy consumption; evaporation losses under high temperature and wind.	[14], [15]
Surface Irrigation	Water flows by gravity over the soil surface.	Low operational cost; minimal equipment requirements.	Uneven water distribution; runoff and percolation losses; lower WUE.	[18], [19]
Drip Irrigation	Water is delivered directly to plant roots via emitters or tubes.	High WUE; reduced weed growth; adaptable to automation and fertigation.	High initial setup cost; clogging issues in emitters; maintenance required.	[16], [17]

2.1 *Irrigation scheduling*

The amount of water and the scheduling abilities determine how the irrigation has to be applied based on timing and volume. In scheduling, the concepts of last date and earliest date are significant. The crop should receive irrigation on or before the last date to minimize the plant's water stress [8]. Poor irrigation scheduling often results in wasteful water and energy usage [20]. Scheduling irrigation involves understanding the proper timing and volume of water application, affecting WUE. Seasonal over-irrigation eliminates WUE. Irrigation scheduling entails a general knowledge of how plants consume water, once such knowledge has been verified with parameters such as weather conditions, growth stage, and canopy temperature [16].

One option is scheduling irrigation based on plant water status. Water status is one of the most accurate representations of the relationship between soil moisture, canopy temperature, stomatal conductance, and weather conditions. Since there are two critical indicators of crop water stress, such as crop canopy temperature and stomatal conductance, these would thus provide an additional purpose in irrigation scheduling [17].

2.2 *Wireless Sensor Networks (WSN)*

Modern farming aims to decrease costs and increase productivity, and precision irrigation is crucial for enhancing food yield and alleviating the workload of farmers [21]. Monitoring in precision irrigation involves gathering information from WSNs to precisely record the actual in-situ plant, soil, and weather conditions within the areas of irrigation [22].

WSN provides a cost-effective and effective solution for numerous applications, such as agriculture and environmental monitoring. It is a technologically advanced paradigm where skills are provided in terms of sensor technology, automatic control systems, digital networks, information storage devices, and data processing strategies [23]. WSNs have been utilized to track diverse agricultural operations, such as modern irrigation systems [24].

2.3 *Internet of Things (IoT)*

The application of technology enables the precise distribution of water required for plant growth. IoT provides an optimal solution for various applications in intelligent water management. Integrating many technologies is in development, essential for its effortless, practical operation [4]. The IoT application in agriculture utilizes objects equipped with devices connected over the internet, including sensors, cameras, flow meters, and others, to measure parameters, such as soil moisture, temperature, humidity, plant images, and weather [21].

To improve water use efficiency, precision irrigation requires the use of new technologies. The overall integration has consistently made irrigation management more efficient by enabling easier-to-use predictive strategies and optimization, as well as systems for detecting, monitoring, and controlling irrigation systems. It additionally takes into account factors that occur in the environment to improve the precision of irrigation systems [16]. IoT-based irrigation systems offer numerous advantages over traditional irrigation systems. They employ various sensors to measure key parameters based on environmental conditions. These advantages include a reduction in water use, lower energy consumption, less crop waste, and lower costs for performance efficiency [25].

2.4 *Automated drip irrigation system*

The automated drip irrigation system combined electronic controllers and weather data in order to predict when to carry out irrigation. The technique aims to save water while reducing non-point source pollution [22]. An automated drip irrigation system increased tomato yield [26] and fruit quality [27] from 8.06 to 6.52 t/ha for the automated control, compared to 6.52 t/ha for the manual control [26]. Moreover, water productivity using a conventional tomato drip irrigation system results in automated irrigation yielding 5.20–12.6 kg.m^{-3} and a benefit-cost ratio of 2.61, compared to 7.7-18.7 kg.m^{-3} for automated irrigation and 2.50, with a water saving of 39.61% [28]. Comparatively, the WUE and IWUE for tomato were 6.50–7.50 kg.m^{-3} in the automated state and 4.70–5.72 kg.m^{-3} in the control; water consumption in automated drip irrigation was reduced by 42% and 15%, respectively, compared to traditional irrigation [29]. The automated drip irrigation system produced 5.6 kg of plants, whereas conventional irrigation produced 4 kg of plants [30]. In conventional irrigation, [31] established that okra yield per plant was 209 g and WUE was 27.68 kg.ha^{-1}, while for sensor-based irrigation, these values were 234 g and 46.76 kg.ha^{-1}.

3 Plant Canopy Temperature

Leaf and canopy temperature measurements are crucial for understanding how plants respond to environmental changes. There are two main methods for measuring leaf temperatures: direct and indirect. Direct methods involve attaching thermocouples to leaves or noncontact temperature measurements utilizing noncontact thermal sensors, such as IRT. In both cases, direct methods measure heat *in situ* on the leaves of intact, living plants. Indirect methods involve destroying plant tissue for laboratory analysis [32].

Water stress effects on plant temperature have been a topic of experimental research since the 1960s. Gates has made significant contributions to the study of plant temperature between 1964 and 1968, explaining the relationships between heat dissipation, transpiration rate, and canopy temperature. By then, several indices had been developed to quantify plant thermal stress, including the temperature difference between the plant canopy and the air, the crop water stress index (CWSI), and the stomatal conductance index. Studies have reported that the CWSI has become the most widely used thermal indicator for assessing plant water status [33], [34]. Concretely, certain features of a leaf temperature sensor are desired in practical use. First, the temperature of the leaf is time-variant, so variations must be applied to the specifications for that particular leaf temperature sensor. It should be ensured that stability is preserved for the leaf temperature sensor under high humidity and high-temperature automatic measurements [35].

Recent articles have indicated that canopy temperature is not a passive measure of air temperature but a dynamic measure of plant physiological responses to air temperature, including stomatal conductance and photosynthetic activity. Early indication of stress associated with drought can be provided using the canopy temperature variability before the symptoms are felt, so that closer scheduling of irrigation can be done. It was found that the computational fluid dynamics (CFD) model of plant factories had revealed that the canopy microclimate variations had a strong effect on the transpiration rate and the heat dissipation concentrated on few locations [36]. These studies indicate the necessity of the spatially resolved temperature data at different levels of the canopy to help improve the precision of irrigation. Similarly, an NTC thermistor thermometer with very high precision was developed and it could achieve a sub-millikelvin resolution, which indicated that a finely-grained temperature sensor could significantly enhance the precision of crop models under controlled conditions [37].

Moreover, the synergy of the most recent remote sensing and AI-based analytics has promoted the understanding of the canopy temperature in the open-field setting. Through multispectral measurements of canopy temperature parameters and thermal imaging and predictive algorithms, it is now possible to measure the canopy temperature dynamics relative to the soil moisture and microclimates. According to the research [11], it has been established that a combination of leaf temperature indices and IoT systems can provide real-time water stress warnings, as well as automated irrigation reactions. These have been achieved in the minimization of the distance between sensor data acquisition and decision-making in precision irrigation through the ability of the large scale farms, as well as the small holder to utilize scalable systems depending on data.

4 The Various Leaf Temperature Measurement

Various studies have measured plant leaf temperature using both destructive and non-destructive methods. Table 2 presents a comparison of different sensors and methods used to measure leaf and canopy temperature. Contact sensors provide high accuracy but are limited to point measurement and require physical contact with plant surfaces. Conversely, non-contact has broader coverage for measurement, although it tends to be subject to environmental influences and complex data processing. This study will introduce and provide a review of infrared temperature, thermal imagers, thermistors, thermocouples, and integrated circuits.

4.1 *Thermistor*

A thermistor has practical applications in various fields of automatic control systems, engineering measurement instruments, and numerous everyday appliances. Utilizing thermistors for temperature measurement typically presents a negative temperature coefficient of resistance, which is the rationale behind NTC thermistors. This means that electrical resistance decreases as the temperature increases. It also doubles up as a temperature sensor and a precise heating source [38].

Thermistors can be used to measure the temperatures of crop canopies with precision. Hence, it provides high precision, similar to contact-type sensors. However, their application is limited to measuring a single specific point [39], [40]. They indicated that the LT-1M sensor is designed for accurate leaf temperature measurements. Each LT-1M assembly comprises a two-channel DC-powered signal conditioner and a leaf temperature sensor. Figure 1 depicts the LT-1M sensor [41].

Figure 1: LT-1M leaf temperature sensor (Thermistor type), which measures leaf surface temperature with high sensitivity and stability, providing accurate data for assessing crop water stress in precision irrigation systems.

4.2 *Thermocouple*

Thermocouples are made of a small bead soldered to two wires of different metal alloys. Due to the thermoelectric effect, the thermocouple bead generates a voltage, resulting in a nonlinear relationship with temperature. Calibration relationships optimize temperature conversion to corresponding measured voltages for thermocouple beads [42]. Thermocouples are often used to measure leaf temperatures, however, several factors must be considered to ensure accurate measurements. *in situ*, thermocouple measurements on the leaves of intact living plants should ensure the thermocouple is not affecting climate variables or thermal properties affecting leaf temperatures, such as solar radiation, leaf angle, and boundary layer growth [32].

Thermocouples have incredible benefits compared to other temperature measurement methods. While many other sensors are currently available on the market, these sensors have their merits in terms of low-level measurement. Type 'T' is an example of a thermocouple made of copper and constantan. This combination is characterized by high stability and is therefore widely employed in low-temperature environments due to its strong oxidation resistance [43].

4.3 *Infrared Temperature*

Infrared thermometers analyze the thermal radiation emitted from its surface to identify the temperature of that surface. The temperature is estimated using emissivity, which is the fraction of emitted radiation, as determined by the Stefan-Boltzmann law. A filter that allows the infrared radiation to pass and the thermocouple that produces voltages correlating with the object's surface temperature [32]. Canopy temperature is commonly measured using single-point radiometric sensors, such as infrared thermometers [44]. Infrared thermometers are inexpensive means of remote, *in situ* measuring leaf or canopy temperatures, with sensor costs amounting to barely a fraction (under 5%) of the total costs incurred in purchasing an infrared camera [45]. However, it offers the standard for non-contact thermography. Thermal monitoring was employed to evaluate plant water status [46]. Canopy temperature was recorded at specified intervals following every ERT acquisition with a handheld infrared radiometer, illustrated in Figure 2 [47].

Figure 2: MI-220 leaf temperature sensor (Infrared thermometer), which captures non-contact leaf and canopy temperature readings, enabling continuous monitoring of plant water status in field and greenhouse conditions.

4.4 *Infrared thermal imaging*

Infrared thermal imaging has gained popularity in agriculture for various applications, including irrigation regulation, crop yield estimation, plant disease detection, and fruit maturity evaluation [48]. These cameras perform imaging and point measurements within a defined field of view. Infrared cameras can provide remote *in situ* measurements of canopy temperatures and have become the de facto standard in noncontact thermography. Despite high costs, the price of infrared cameras has dropped by at least 50% over the last decade to a modest resolution of 640 × 480 pixels [32].

With technological advancements, portable thermal cameras have become increasingly applicable for monitoring plant water status. Nowadays, infrared cameras are considered key tools in determining the spatial distribution of canopy temperature (Tc), thereby aiding in the calculation of the crop water stress index [49]. Thermal imaging cameras are increasingly important in agriculture for monitoring plant health, scheduling irrigation, detecting diseases, estimating crop yield, evaluating water distribution in drip irrigation systems, and measuring canopy temperature [50]. Several studies have documented the use of a handheld IRT for measuring canopy temperatures, including the FLIR E8-XT, shown in Figure 3 [28].

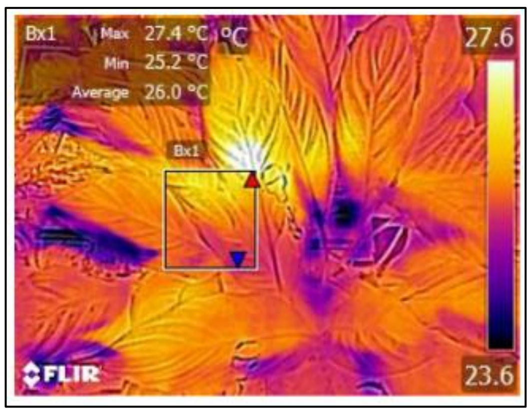

Figure 3: Thermal image captured using the FLIR E8-XT infrared camera. The non-contact canopy temperature mapping and spatial visualisation of plant stress that this device gives an early indication of water deficiency, which helps in precise irrigation scheduling.

4.5 *Integrated circuit sensor*

Real-time temperature measurements ensure lightweight and fast systems function within an acceptable thermal range. Recently, integrated circuit (IC) temperature sensors have been used to monitor hot spots in both external and internal components precisely. Unlike traditional temperature sensors, such as resistance temperature detectors, thermistors, and thermocouples, these sensors offer several advantages. More importantly, it eliminates the need for linearization and cold-junction compensation. It often provides cold junction compensation for thermocouples. These devices usually improve noise immunity due to their higher output signals, with certain modifications to logic outputs that enable direct interfacing with digital systems [51].

The LM35 is a versatile and reliable temperature sensor IC that provides an output voltage linearly proportional to temperature in °C. This output passes through an amplifier with a gain of 3.5 to the analog-to-digital converter pin P0.13/AD1.4 of the LPC2148 [52]. As depicted in Figure 4, the LM35 has three pins: voltage input (VIN), voltage output (VOUT), and ground (GND). The pins are used to measure the temperature and transmit a voltage output signal to a microcontroller [53].

Figure 4: LM35 temperature sensor labelled as VIN (Voltage Input), VOUT (Voltage Output), and GND (Ground), used for direct leaf temperature measurement because of its low cost, accuracy, and linear output.

Table 2: Comparative advantages and disadvantages of leaf and canopy temperature measurement.

Method / Sensor Type	Measurement Type	Advantage	Disadvantage	Application	Ref.
Thermistor	Contact	High accuracy, low cost, sensitive to small changes, suitable for point measurement	Affected by self-heating and wiring resistance; limited to one point	Laboratory and small-plot experiments	[38]–[41]
Thermocouple	Contact	Simple design, robust, wide temperature range, fast response	Requires direct contact; easily detaches from leaves; local measurement only	Tree canopies, controlled environment studies	[42], [43]
Infrared Thermometer	Non-contact	Cost-effective, simple to deploy, suitable for outdoor use	Single-point measurement; affected by emissivity and sunlight	Field and greenhouse canopy monitoring	[44]–[47]
Infrared Thermal Imaging	Non-contact (spatial imaging)	Provides canopy-wide temperature mapping; enables CWSI calculation	High cost; complex calibration; data-heavy	Irrigation scheduling and crop stress mapping	[48]–[50]
Integrated Circuit	Contact (analog/digital output)	Linear output, easy to integrate with IoT systems, low power use	Sensitive to sunlight heating; may damage delicate leaves	IoT-based smart irrigation and embedded systems	[51]–[53]

5 Application and Methods of Leaf and Canopy Temperature Measurement

In this section, this study will discuss the various applications and methods for measuring leaf temperature, including infrared thermometry, thermal imaging, thermistors, thermocouples, and integrated circuits. Table 3 summarizes the technological parameters, findings, advantages, and disadvantages.

5.1 *Infrared Temperature*

Infrared temperature pertains to measuring an object's thermal condition through an infrared thermometer, which detects and measures the infrared radiation emitted by the object. A study [42] utilized an MI-220 model; the device was attached to a pole held at a fixed angle of 90° from vertical and maintained a 30 cm distance during the canopy measurements. A portable infrared radiometer measured the canopy temperature at different intervals after each effective radiant temperature acquisition. At 30-cm intervals, the canopy temperature measurements were taken at every three electrodes. Sky temperature data were collected at each measurement time step to derive adjusted canopy temperature values.

Canopy temperature was measured with wireless infrared thermometers set on a fixed mast in each experimental plot, following the method described by [54]. The IRT had a 20-degree field of view and an accuracy of 0.5 °C, thus avoiding the need for sensor calibration. Every 10 seconds, the canopy temperature was recorded and averaged for 30 min with the weather station recordings.

5.2 *Infrared thermal imaging*

This study intended to assess the extent to which different irrigation strategies can cause a change in the canopy temperature and, therefore, the condition of the plant from a thermal infrared camera perspective [55]. The continuous process of thermal imaging greatly aids the estimation of plant water stress and health relative to other environmental and irrigation variables. The study [48] included four potted *Hibiscus* plants under different treatment levels of slight, mild, moderate and severe water stress. The FLIR E6 handheld thermal camera was used to capture thermal images of various heated canopy zones from the frontal, top, left-side, right-side, and front-facing angles. The study [56] involved measuring plant canopy temperatures using an Everest 100 L model infrared thermometer. In the IRT's field of view, the soil was angled 30–40° from the horizontal plane toward the plant's surface to keep out soil surface information. Therefore, it can be concluded that CWSI can aid irrigation scheduling and crop yield estimation.

Another study [57] utilized the FLIR A35 (FLIR Systems, USA) in a similar way. Measurements were taken on leaves positioned in the mid-upper layer of the canopy at midday. To determine plant hydration levels, grapevine-derived canopy temperatures (Tc), acquired through thermal imagery, were used to formulate the crop water stress index and the stomatal conductance indicator. Further study [49] utilized an FLIR E8 thermal camera to take infrared images at 2:00 PM on clear days. Images were captured at sunlit sections with a 30-degree angle from the top of the canopy, ensuring the entire canopy was imaged. This process took place on three selected sunny days during each of the vine's growth stages. Thermal cameras, especially in determining CWSI values for crop water stress analysis, have proven effective whenever suboptimal temperature influences are ignored.

5.3 *Thermistor*

A thermistor is a special type of resistor that changes resistance as temperature changes. A leaf temperature sensor LT-1M was applied and recorded the temperature of the plant's leaf at 1 and 2 meters above the growing medium [58]. In another study [39], data were recorded every 5 min from an LT-1T device attached to a plant leaf. The study provides leaf temperature readings, which are crucial in assessing the health of the plants monitored. The LT-1M is a sophisticated glass-encapsulated thermistor that has been miniaturized and designed as a touch probe for more accurate leaf temperature measurement. The sensor has a wide range of temperature measurement capabilities, from -5 to +50 °C, with a typical accuracy of ±0.08 °C. A stainless steel wire clip of negligible mass is used for attachment [59].

5.4 *Thermocouple*

Thermocouples use conduction to determine the temperature of the leaves from the inside, until reaching the thermocouple bead. In this respect, thermocouples become practical devices for measuring leaf temperature within the dense interiors of clusters and canopies, where non-contact techniques are limited [32]. In study [58], Type T thermocouples were used, where 24 of the sensors were divided into three sections of different segment canopies, to measure the leaf temperature of a Noble fir's leaf temperature. The lower two sections were in the lower right part of the observation area, and were the first and second clusters. A third cluster was placed centrally in the middle, and these were the Tertiary clusters. These positions were determined in consideration of the ease of access and the different light conditions around the area.

Table 3: A comparative summary of temperature sensor technologies for irrigation.

Method	Sensor	Range & Precision	Advantage	Limitations/ Trade-offs	Cost & Scalability	Durability / Ease of Use	Crop	Finding	Ref.
Infrared temperature	MI-220 model SI-121	-50 to 80 °C - ± 0.2 °C	Portable Flexible Relatively inexpensive	Affected by weather conditions Less accurate Regular cleaning	Low cost; moderate scalability	High ease of use; moderate durability	Tomato	Early morning and seven hours after the irrigation phase started had lower CSWI values than the day's hottest hours.	[41]
	SapIP-IRT, Dyna max, Houston, Tex.	Up to 25 SapIP nodes – 5,000 ft away	Wireless Scalability Compatibility	Cost Less accurate	High cost; highly scalable	Durable; requires technical setup	Corn	The T100 (100% soil water replenishment) treatment had lower CWSI and higher yield values than T66 and T33, with most CWSI values >0.2, indicating plant water stress.	[54]
Infrared thermal imaging	FLIR E6 handheld thermal camera	-20 °C to +250 °C - ±2 °C	Easy to use Wide field of view	Lower resolution Expensive	High cost; limited scalability for small farms	Moderate durability; user-friendly interface	Hibiscus	T4 (250 mL) has no water stress at 23–30 Celsius, and CWSI 0.8 shows plant water stress reduction.	[48]
	Everest 100 L model infrared thermometer	-40 °C to +100 °C - ±0.5 °C	High accuracy Fast time response	Affected by emissivity Expensive	Medium–high cost; scalable for research	Durable; easy calibration required	Black cumin	Black cumin plants need to be irrigated when 0.08 to 0.12 CWSI is reached. Maximum yield (692 kg/ha) with I100 (276 mm water applied) treatments	[56]
	FLIR E8, USA	-20 °C to 550 °C - ±2 °C	Dust and water resistance User-friendly interface	Image quality	Very high cost; scalable for large farms	Highly durable; requires a trained user	Rice	At the vegetative to reproduction stages, the optimal CWSI ranged from 0.556–0.569, 0.481–0.486, 0.571–0.641, and 0.511–0.606.	[49]
Thermistor	(LT-1M, Bio instruments S.R.L., Chisinau, Moldova)	0 to 50 °C - < 0.15 °C	High accuracy Lightweight Durable	Potential for leaf damage	Low cost; high scalability	Durable; easy to maintain	Paprika	The fresh weight, thickness, firmness, volume, sugar content, and acidity of fruits were significantly greater in plants treated with S1 (Single Screen) than those treated with S2.	[39]
Thermocouple	Type T thermocouples (diameter: 0.13 mm; Omega *et al.*, Stamford, CT, USA)	-270 to 400 °C - ±0.5 °C	Wide temperature range Durable Cost-effective	Corrosion Limited accuracy	Low cost; scalable for field studies	Highly durable; moderate ease of use	Noble fir	Thermocouples are challenging to install in tree canopies and easily detach from leaves, making field tests of leaf temperatures challenging. Exemplary thermocouple connections on needle leaves are difficult to attach.	[58]

5.5 *Integrated circuit*

An integrated circuit (IC) is a general term for the devices formed on a semiconductor wafer, which contains several million smaller combinations of resistors, capacitors, and additional components. The LM35 is an example of an IC employed to measure temperature. The LM35 temperature sensor, according to [60], is a precision integrated circuit device with an output that is directly proportional to the temperature being measured in °C. The sensor circuitry has been immersed in a protective substance to prevent oxidation and other processes. Providing a more accurate measure of temperature than a thermistor, it has minimal self-heating, ensuring the temperature never rises beyond 0.1 °C in still air. Its operating temperature ranges from -55°C to +150 °C.

A study by [61] utilized the LM35 to measure canopy temperature for irrigation scheduling purposes. Due to its accuracy, cost-effectiveness, and low self-heating, the LM35 was chosen for leaf and air temperature sensing. Four LM-35 sensors were installed on each plant; two were attached to sunlit leaves, while the other two were on the shaded. Two of the four sensors were attached to the bottom of the leaf using a clip device, one on the sunlit side and the other on the shaded side. Two more sensors were attached to either side of the plant to simulate ambient air temperature.

6 Emerging Issues and Challenges

The emergence of irrigation scheduling technologies employs a plant-based approach, including the measurement of canopy temperature. CWSI is primarily used as a thermal indicator to assess a plant's water status. Despite their advantageous contributions and applications in agriculture, particularly irrigation scheduling, non-contact and contact devices have encountered specific challenges. The following highlights present the limitations as follows.

6.1 *Infrared temperature*

This is crucial for infrared thermometers, which do more than just measure the emitted energy from an object's surface. The infrared thermometer also measures energy emitted from other sources and the energy reflected or transmitted toward the instrument's target. The difference can lead to errors in data collection [49]. Moreover, the effect extends over longer distances and remains uncontrolled during propagation, as it does not contribute to the heat-transfer coefficient of the medium through which the energy is emitted. When assessing leaf-surface temperatures, measurements are typically limited to one spot on the leaf surface. While this method offers valuable data, it falls short of capturing spatial variations across the entire crop canopy [62]. Contrarily, thermal imaging devices can be affixed to field equipment as IR thermometers, however, single-point sensors lack the panoramic resolution that thermal cameras provide it [63].

6.2 *Infrared thermal imaging*

Continuous thermal imaging provides invaluable insight into how irrigation and environmental variables affect crop water stress and the overall health of plants. However, thermal time-lapse cameras capable of continuous, in-field monitoring of water stress currently seem lacking and are expensive [49]. Furthermore, a portable thermal camera ensures mobility but poses challenges to regular canopy temperature measurement. Such stationary thermal imaging cameras will allow for frequent measurement but incur an extra cost [39].

6.3 *Thermocouple*

The continuous measurement of leaf temperatures by thermocouples in field studies, especially without continuous monitoring, presents significant challenges. Installing thermocouples in tree canopies complicates the data collection, as they easily detach from leaves and malfunction. Attaching thermocouple junctions to needle leaves presents considerable difficulties, as many often detach shortly after installation. Thermocouples encountered high uncertainty due to spurious junction voltages, inadequate voltmeter sensitivity, cable drift, and reference temperature uncertainties [58]. The primary limitations of thermocouples are their inability to measure average temperatures over large areas and the requirement for direct contact with the thermocouple bead through leaf-bolting means. This can pose considerable challenges, particularly when application methods require long-term measurements under open-air weather conditions [32].

6.4 *Thermistor*

Thermistors work by changing their electrical resistance with temperature. Due to the use of current for measurements, self-heating occurs, resulting in readings recorded at temperatures above the actual leaf temperature. This effect is more pronounced at higher currents, hence the need for careful circuit design and accurate calibration. Stretching wires connecting the thermistor to the measuring device will add resistance that distorts the signal noise, which could result in significant inaccuracies. The main feature of the thermistor is its dependency on its functional nature, whereby its variance concerning temperature is never linear [64]. A complex calculation is necessary to determine the leaf's temperature accurately.

6.5 *Integrated Circuit*

The application of the Integrated Circuit (IC) sensors, such as LM35, which are described as highly linear, inexpensive and compatible with digital monitoring systems, has rendered precision irrigation impossible. The LM35 has a proportional output voltage to the temperature in °C and is not required to be externally calibrated, making it the best fit to be used in IoT applications. The present-day state of IC sensors is marked by the combination of both digital-to-analog converters and low-noise amplifiers that can reach the accuracy of sub-degrees even under unstable field conditions [37]. Its low power consumption (it does not exceed 60 uA) renders the LM35 appropriate in the long run in wireless sensor networks, particularly when small solar or power harvesting systems are used to power it.

Recent studies indicate that modules based on LM35 are useful in open-field surveillance. Indicatively, an LM35-driven irrigation was developed to access real time data on the temperature of leaves and could auto-activate the pumps in case of a threshold exceedance, which conserved 28% of water [12]. However, it also has some environmental issues: direct sun rays can cause signal drift, and the possibility of fixing it on a leaf is so fragile due to the rigid structure of the sensor. Hence, in order to be precise in measurements, protective shading enclosures and soft-clamp mounts must be employed. A future perspective of low-cost scalable irrigation monitoring solutions for smallholders as well as large-scale businesses is hybrid IC modules with LM35 and microcontrollers (e.g., ESP32) and AI-based calibration algorithms.

6.6 *Sensor calibration challenges*

The fundamental parameter of the sensors required would be calibration, so that there would be proper temperature measurements, particularly in agricultural environments where a minor variation would cause a major interference with the irrigation decision. Measurement stability and sensor performance could be influenced by numerous environmental factors such as humidity, solar radiation and canopy structure. One such case is that the humidity changes affect the sensitivity and the response time of capacitive soil and temperature devices, increasing the discrepancy in field accuracy [65]. These dynamic interactions in the environment are not often discriminated by the traditional ways of calibration. The developments of the calibration algorithms using machine learning tactics are current and dynamic when it comes to rectifying such variables, increasing the accuracy of the real-time measurements [66]. Moreover, the cover of canopies and the orientation of leaves can also disrupt sensor visibility, and it complicates the calibration process [67]. The use of edge-computing models makes it possible to adapt sensor values on-the-fly, which facilitates locally recalibrating sensor data without the help of cloud applications alone. The calibration systems are spread in a way that it scale-up and enhance data integrity in large farming areas.

6.7 *Environmental influences*

Humidity, radiation intensity, and canopy geometry also play a crucial role in the sensor accuracy and are considered to be the environmental factors [36]. Unstable ambient properties can cause the emissivity error in infrared thermometers and thermal cameras, whereas dust and water droplets give rise to a decrease in optical signal quality. The reduction of these effects in recent applications of the field [37] consists of radiation shields, spectral correction algorithms, and spectrally-compensated calibrations. Matched humidity sensors, and light sensors are also being used together with thermistor-based and IC-based sensors with an aim of providing contextual correction so as to ensure that the temperature information is normalized to the local variations in the microclimate. All of that results in increased sensor reliability in the variable field scenario, where precision irrigation achieves the level of predictable, data-driven functionality.

6.8 *Maintenance and cost barriers*

Despite the accurate benefits of the advanced sensing technologies, there are still maintenance needs and high start-up costs, which inhibit the use of the sensing technologies. Particularly, such systems are financially constrained to smallholders [68]. The need to change broken parts, power control, calibration, etc., is considered a routine maintenance process, which increases the operational cost, which also leads to financial pressure [69]. The low-cost sensors, such as LM35 and the DS18B20, may be cheaper at the start, but the stability and the need to recalibrate on a schedule are issues [70]. Successful usability of complex IoT systems is also limited by the low level of technical literacy [71]. All these arguments justify why there is a need to have convenient sensor interfaces and training programs that are easy to use and are capable of enabling farmers to use smart irrigation systems in a sustainable way.

6.9 *Integration with IoT and WSNs*

Temperature sensors combined with Internet of Things (IoT) and Wireless Sensor Networks (WSNs) are one of the most radical modifications in precision agriculture [72]. IoT plans permit real-time collection and the transfer of information in time so that automated irrigation choices, contingent upon the temperature of the canopy, the moisture of the soil and the weather, can be made. To give an example, IoT-based smart irrigation systems are effective in turning on or off the water based on the sensor data and, in this manner, will save a lot of water that is going to waste and increase crop production [68]. However, the connection problem, power stability, and data security in rural areas continue to exist [73]. Engineering, agronomists and software developers would also be important in order to address them [74]. These partnerships can inspire the development of less intricate interfaces, greater standards of communication, and deployable frameworks that can be tailored to the particularities of local farms.

7 Technological Advances Addressing Barriers

7.1 *Cost*

Reduction of cost is one of the best achievements of recent developments. The low-cost capacitive and resistive sensors have made precision irrigation (even in small-scale farms) possible. They also measure soil temperature and moisture accurately and are inexpensive and simple to network, as these sensors can be easily interconnected [25]. When combined with wireless communication systems, these technologies enable farmers to develop cost-effective, data-driven irrigation networks that can replace conventional, labor-intensive irrigation practices [75].

7.2 *Accuracy*

A sensor was developed based on vanadium-oxide-doped, which can provide the correct temperature readings even when the humidity changes and can provide useful information on the condition of the soil and the actions of nitrogen [76]. It contributes to the optimization of the irrigation schedule and minimizes the effect of climate fluctuation [77]. Its connection with IoT systems also increases its accuracy, because it is also possible to track any changes and control feedback [78]. These mechanisms are useful in preventing excessive irrigation and waste of resources that cause water to be distributed where and when it is required.

7.3 *Scalability*

Another significant development is scalability. WSNs are now included in a range of temperature sensors found everywhere in extensive fields of agriculture and provide full access to information on the surrounding location [79]. The IoT system poses the possibility of simply combining the data and controlling the irrigation on an adaptive basis [80]. It is also thought that the low-power communication protocols and routing energy efficiency will further enable the operation to be elevated in terms of sensor performance [81] and enable the reliability of the devices in the off-grid or resource-heavy regions. These include technological innovations, which overcome the problem of scalability that made precise irrigation in developing regions difficult in the past.

8 Conclusions

The drip irrigation systems under the vegetative concepts will be automated and this is an important step towards the reduction of the wasteage of irrigation since each plant receives the amount of water required. Among the existing technologies of temperature sensing, Infrared thermography (IRT), thermal imaging, thermistors, thermocouples, and integrated circuit (IC) sensors have their advantages and disadvantages.

"Infrared thermal imaging and infrared thermometry (IRT) sensors are among the most promising technologies for realizing precision irrigation, as they can capture spatial variations in canopy temperature across entire plant surfaces, enabling a comprehensive assessment of crop water stress. However, these technologies are expensive and require substantial maintenance, making them unaffordable for smallholder farmers. Consequently, they are more feasible for large-scale commercial farms, where the investment can be justified by increased productivity through advanced data infrastructure and automated systems.

The LM35 and thermistors could be an alternative to contact-based sensors due to their low-cost and portability, and also due to their acceptability with regard to site-specific irrigation control. Such low-cost IoT-enabled sensors can be applied to facilitate scalable smart irrigation services, which are cost-effective and technically accessible.

Future research should emphasize the integration of multisensor systems that combine thermal, soil moisture, and atmospheric data to enhance the quality of decision-making. Irrigation scheduling and early detection of crop water stress can be further optimized through the application of artificial intelligence (AI) and machine learning algorithms that process multidimensional sensor data. Moreover, extensive field testing under diverse environmental conditions is necessary to validate sensor stability, calibration accuracy, and economic feasibility across different cropping systems. In conclusion, a critical next step toward realizing the full potential of precision irrigation for sustainable and resilient agriculture is the development of low-cost temperature sensing technologies with improved interoperability and adaptive intelligence.

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Author Contributions

V.A.: conceptualization, writing-original draft preparation, and writing-review and editing; J.P.S.: reviewing and checking; W.C.: reviewing and checking; S.B.: reviewing and checking. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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