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Feasibility study on Lepton 3.5 in terms of accuracy for measuring leaf temperature of crops

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Abstract

The precise monitoring of leaf temperature is becoming more important as crop leaf temperature is utilized more frequently for different uses such as irrigation, disease and pest detection. This study aims to explore the potential usage of a cost-effective Lepton 3.5 camera to measure the crop canopy temperature. The accuracy of the Lepton 3.5 will be compared to a FLIR E8-XT thermal camera and an MLX90614 infrared thermometer. With the usage of three devices: a custom Lepton 3.5 camera, an Implexxio LT-1T thermistor and an MLX90614, the temperature of the target leaf of a laboratory plant was automatically measured every five minutes. The data would then be recorded on a private cloud server and manually measured with a handheld FLIR E8-XT. The performance of these three devices was evaluated to the standard of a highly accurate Implexxio LT-1T thermistor using the mean absolute error and root mean squared error. Among the non-contact sensors- MLX90614, Lepton 3.5 and FLIR E8-XT- the MLX90614 sensor showed the highest accuracy. However, the Lepton 3.5 module had an accuracy of less than ±2°C, which was similar to FLIR E8-XT and much better than the error value specified for the Lepton. The low-cost Lepton 3.5 can be used to periodically measure leaf temperature with an accuracy comparable to that of an intermediate-level thermal imager.

Key words: Leaf temperature, CWSI, Accuracy, Lepton 3.5, FLIR E8-XT, MLX90614

Introduction

Leaf temperature is defined as the surface temperature of a crop leaf. It influences the photosynthesis and transpiration of crops and is also a critical indicator for determining crop moisture status and health. Insufficient soil moisture hinders the crops to transpire, causing stomatal closure and increased leaf temperature. Research in the past (Su *et al.,* 2020; Yang *et al.,* 2021; Ballester *et al.,* 2013; Berger *et al.,* 2010; Chaerle *et al.,* 1999) used crop canopy temperature to assess the stomatal conductance/closure, drought and pest stress. Like such, accurate monitoring of leaf temperatures during crop cultivation is becoming more important.

Leaf temperature can be measured through either contact or non-contact methods. Contact methods (Blad *et al.,* 1976; Pieters *et al.,* 1972) such as thermocouples and thermistors provide high accuracy but require multiple sensors to measure canopy temperature. On the other hand, Non-contact methods such as infrared thermometers (Kumar *et al.,* 2021; Luus *et al.,* 2022; Jones *et al.,* 2018; Martinez *et al.,* 2017; Sui *et al.,* 2012; O'Shaughnessy *et al.,* 2011; Dhillon *et al.,* 2012) and thermal imaging cameras (Su *et al.,* 2020; Leinonen, 2004; Blaya-ros, 2020) provide lower accuracy, with infrared thermometers limited to measuring broader areas and thermal imaging cameras having even lower accuracy than infrared thermometers. Handheld infrared thermometers are mobile but not practical for regular monitoring. In the past, thermocouples, thermistors, and handheld infrared thermometers were commonly utilized despite each having its own limitations. Nowadays, fixed infrared thermometers and thermal imaging cameras have become the prevailing methods for measuring leaf temperature.

Infrared thermometers measure thermal radiation emitted by the surface and can determine the temperature of the detector within a certain range of its actual temperature. They commonly use a spectral band of 8 to 14 µm. In some studies, (Hatfield; 1990; Alves *et al.,* 2000; Ahi *et al.,* 2015; Kumar *et al.,* 2021), portable infrared thermometers have been used to measure leaf temperature and calculate the Crop Water Stress Index (CWSI). Thermal infrared imaging cameras detect and measure infrared energy emitted by objects, then visualize the data. Each pixel in the sensor array has a temperature value that creates a color map when focused on an object.

Many studies have used handheld thermal cameras to measure leaf or canopy temperature. Sui *et al.* (2020) used a handheld thermal infrared camera to measure forest canopy temperature, while Luus *et al.* (2022) used the same camera to measure the grapevine leaf temperature. However, fixed thermal imaging cameras can be very expensive. As a substitute, the low-cost FLIR Lepton module has been used to replace a fixed thermal camera. Some studies (Arcosi *et al.,* 2020; Baker *et al.,* 2019) have utilized the Lepton 3.5 module to monitor canopy temperature.

In general, the CWSI is computed using Equation:

$$\text{CWSI} = \frac{(T_c - T_a) - (T_c - T_a)_u}{(T_c - T_a)_{ul} - (T_c - T_a)_u}$$

T_c measures canopy temperature, T_a stands for air temperature, $(T_c - T_a)_u$ and $(T_c - T_a)_{ul}$, each are the lower bound and upper limit, respectively (Idso *et al.,* 1981; Jackson *et al.,* 1981, 1988).

Canopy temperature is a crucial variable in calculating a CWSI. If the device used for measuring the canopy temperature has low accuracy, the results of the CWSI value will be full of errors as well. Therefore, it is crucial to use accurate and reliable measurement devices when calculating the CWSI.

Accurate measurement of leaf or canopy temperature is important as well for improving crop water stress assessments. However, many studies use thermal imagers with factory calibration, without considering the potential errors of the sensors. This study aims to show the usability of a low-cost Lepton 3.5 thermal imaging camera (Kim, 2021) using a warm-up time that can offer the same accuracy as an intermediate-level thermal imager in measuring canopy temperature for researchers. This study will be valuable for researchers seeking a cost-effective, accurate solution for monitoring crop water stress.

Materials and methods

Environment monitoring system design: Figure 1 depicts the data acquisition system used for leaf temperature measurement. The system consists of a private cloud server with MySQL 8.0, Mosquitto broker 2.0, Grafana 9.0 and Node-RED 1.3. The system uses a long-range (LoRa)-based wireless sensor network that is connected to the Internet via Long Term Evolution (LTE) or Ethernet, to monitor the leaf temperature measured by thermistors and infrared thermometers in real-time. The custom Lepton 3.5 camera is connected to the gateway also via Wi-Fi or Ethernet. The gateway serves as a sink node of the wireless sensor network and converts this data into JavaScript Object Notation format. Then, it transmits to the cloud server utilizing the Message Queuing Telemetry Transport (MQTT) protocol. However, the camera itself transmits the data directly to the cloud server using the MQTT method without any gateway relay.

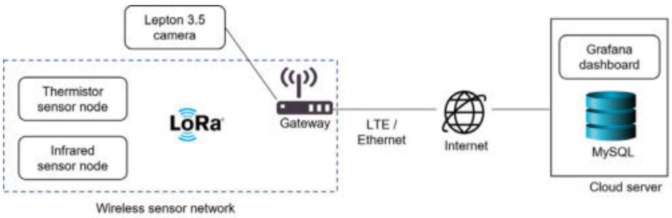

Fig. 1. Architecture of the monitoring system designed for leaf temperature measurement

Table 1 shows the specifications of each node in the data acquisition system for leaf temperature measurement. The sensor node includes an ATmega 328P microcontroller with a clock speed of 8 MHz, a HopeRF RFM95W transceiver operating at 915 MHz and an operating voltage of 3.3 V. The Lepton 3.5 camera node is based on a Raspberry Pi Model 3 running on Raspbian 9.0 operating system and connected to the internet via Ethernet. The gateway node also uses a Raspberry Pi 3 Model B with Raspbian 8.0 and an RFM95W transceiver.

In Figure 2, the LT-1T (Implexx Sense, Melbourne, Victoria, Australia) is connected by SDI-12 (Serial Digital Interface at 1200 baud) and the MLX90614 is connected to the ATmega328P by the I2C (Inter-Integrated Circuit) communication protocol. Power consumption is saved by applying the sleep mode of the microcontroller and RFM95W module.

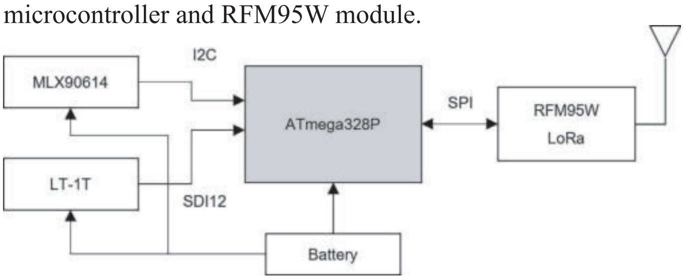

Fig. 2. Block diagram of the sensor node architecture

Table 1. Technical specifications of the nodes

Node	Board specific features	
Sensor node	Microcontroller	ATmega328P
	Operating voltage	3.3 V
	CPU clock speed	8 MHz
	Transceiver	915 MHz RFM95W
Lepton 3.5 camera node	Board	Raspberry Pi Model 3
	Operating system	Raspbian 9.0
	Internet connection	Ethernet
Gateway node	Board	Raspberry Pi Model 3
	Operating system	Raspbian 8.0
	Transceiver	915 MHz RFM95W
	Internet connection	Ethernet

Experimental setup: The Implexx thermistor, MLX90614 infrared thermometer, FLIR Lepton 3.5 and FLIR E8-XT radiometric thermal camera were used to compare the error and precision of the sensors for leaf temperature measurement. Details are provided in Table 2.

Table 2. Technical specifications of sensors

Model	Implexx LT-1T	FLIR Lepton 3.5	FLIR E8-XT	MLX90614-DCC
Measurement method	Thermistor	Radiometric	Radiometric	Infrared
Resolution		160 x 120 pixels	320 x 240 pixels	
Measurement Range	-5 ~ 50 °C	High gain mode: -10 ~ +140 °C	High gain mode: -20 ~ +250 °C	-70 ~ +380
Accuracy	±0.08 °C	±5 °C or 5%	±2 °C or 2%	±0.5 °C
Field of view		57° × 71°	45° × 34°	35°
Spectral Range		8 ~ 14 μm	7.5 ~ 13 μm	5.5 ~ 14 μm
Sensitivity	0.15 °C	0.05 °C	0.05 °C	0.02 °C
Supply voltage	5 ~ 24 VDC	1.2, 2.8, 2.5 ~ 3.1 V		3 ~ 5 V

LT-1T (Implexx Sense, 2022) is a high-precision, glass-encapsulated thermistor, used as a subminiature touch probe to measure leaf temperature. It is the most accurate sensor compared to others as it can detect a wider range of -5°C and +50°C and also has a high accuracy of ±0. 08°C. The thermistor also comes with an easily attachable lightweight stainless steel wire clip.

FLIR's Lepton 3.5 (FLIR Lepton, 2022) with radiometry is a long-wave infrared camera module. The camera measures the surface temperature by examining the intensity of the infrared signal. FLIR's Lepton 3.5 with radiometry is a camera module that operates in the long-wave infrared spectrum. It measures the surface temperature through the camera and analyzes the intensity of the infrared signal.

FLIR E8-XT (FLIR E8-XT, 2019) has a resolution of 320 x 240 pixels, a radiometric accuracy of ±2 °C or 2 % in high gain mode, a thermal sensitivity of 0.05 °C and a FOV of 45° × 34°. The MLX90614-DCC infrared thermometer has an accuracy of 0.5 °C in a wide temperature range of 0 ~ +50 °C for both air and object temperature, a measurement resolution of 0.02 °C and a FOV of 35°. The MLX90614-DCC infrared thermometer has an

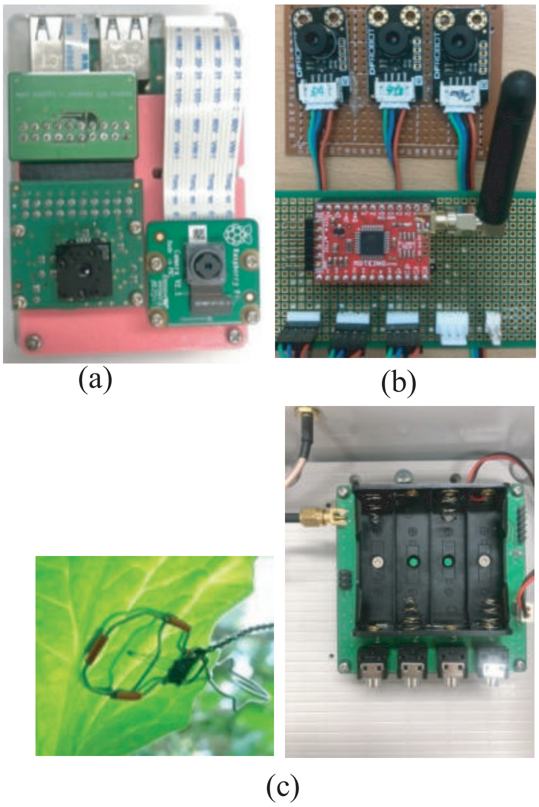

Fig. 3. Prototype: (a) thermal-RGB camera (Kim, 2021), (b) infrared thermometer, (c) LT-1T and custom sensor node (Kim, 2023)

accuracy of 0.5 °C in a wide temperature range of 0 ~ +50 °C for both air and object temperature, a measurement resolution of 0.02 °C and a FOV of 35°.

The prototype imager (Kim, 2021) of Figure 3(a) consists of a Raspberry Pi 3 Model B, FLIR Lepton 3.5 and a Raspberry Pi Camera Module V2.1. The infrared thermometer prototype is composed of three MLX90614s shown in Figure 3(b). Thus, Figure 3(c) displays the LT-1T sensor and a custom LoRa sensor node.

Figure 4 shows a schematic overview of the experimental setup. The experiment was conducted indoors on Peace Lily plants. LT-1T sensors were installed on both leaves and the back side of the leaf was measured. The MLX90614 sensor was installed 3 cm low on the back of one leaf and measured in three spots. A Lepton 3.5 camera was installed above the plants and canopy images were recorded.

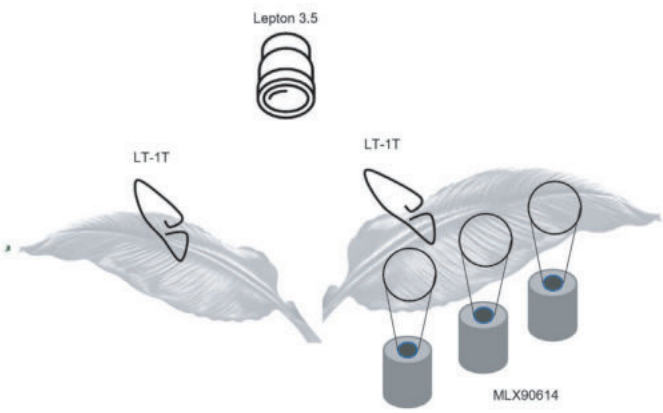

Fig. 4. Experimental setup

Equation (2) is used to calculate the mean temperature of Lepton 3.5 using the temperature values of each pixel in a 160 x 120 array (FLIR LEPTON Engineering Datasheet, 2022).

$$MLT = \frac{1}{NM}\sum_{i=0}^{N}\sum_{j=0}^{M}\frac{T_{ij} - 27315}{100} \tag{2}$$

MLT=Mean Lepton Temperature

N and M are the row and column values of the thermal image, respectively. T_{ij} represents the target temperature of the i_{th} row and j_{th} column pixel.

As shown in Figure 5(a), to calculate the leaf temperature from the canopy image of Lepton 3.5, a rectangular area was designated at the location of the leaf to which the LT-1T was installed and also, the temperature values within the area were averaged. FLIR E8-XT measurements were conducted at different times. Once the canopy was recorded by the camera, the images were processed in the FLIR Thermal Studio (Teledyne FLIR, Wilsonville, OR, USA) to obtain the leaf temperature from the LT-1T installed region.

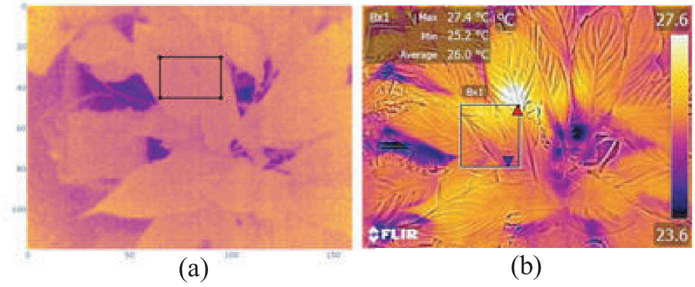

Fig. 5. Thermal images: (a) Image by Lepton 3.5 (b) Image by FLIR E8-XT

The experiments took place in a laboratory from May 1st to September 30th. Data, except for the FLIR E8-XT, were measured by the sensors every five minutes during this time and were recorded on a cloud server. To compare the error of the sensors, the recorded data were compared with the value of the LT-1T, since it had the highest accuracy among other sensors.

The mean absolute error (MAE) and root mean squared error (RMSE) are used as the measure. The MAE and RMSE are calculated using equations (3) and (4).

$$\text{MAE} = \frac{1}{N}\sum_{i=1}^{N}|x_i - y_i| \tag{3}$$

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - y_i)^2} \tag{4}$$

In these equations, N is the number of measurements, i is the index of each measurement, x_i represents the measured values by LT-1T and y_i represents the measured values by a compared sensor.

Results and discussion

Comparison of two leaf temperatures with LT-1Ts: Between May 10 and May 25 of 2022, leaf temperatures were measured using LT-1T sensors, which were attached to each of the two leaves (as shown in Figure 6), with an accuracy of ±0.08 °C. The two graphs show similar patterns, with some data points showing abrupt changes that corresponded to significant variations in the laboratory temperature, likely caused by the opening of the laboratory door.

The data collected are summarized in Table 3. The minimum,

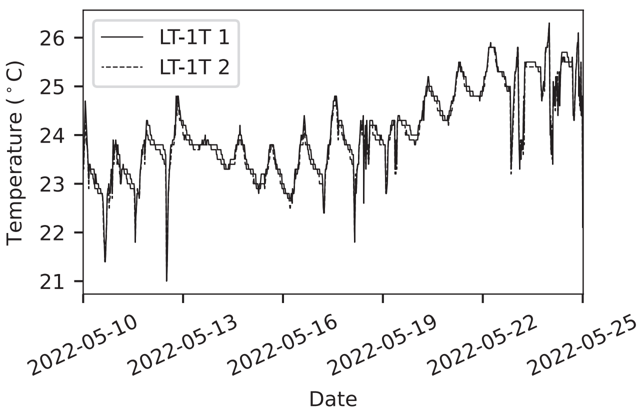

Fig. 6. Comparison of leaf temperature measurement from two LT-1T devices across experimental days

maximum and average leaf 1 temperatures are 21.0 °C, 26.3 °C and 24.1 °C. The minimum, maximum and average leaf 2 temperatures are 21.3 °C, 26.3 °C and 23.99 °C, respectively. The MAE of the two leaf temperatures is 0.18 °C and the RMSE is 0.21 °C, indicating that there is little difference in temperature between the two leaves.

Table 3. Comparison of two leaf temperatures using LT-1T

Date	Target	Min	Max	Mean	MAE	RMSE
2022.5.10~ 2022.5.25	Leaf1	21.0	26.3	24.1	0.18	0.21
	Leaf2	21.3	26.3	23.99		

Comparison of LT-1T and FLIR E8-XT: Leaf temperature was measured with both LT-1T and FLIR E8-XT for one leaf divided into three periods from July 13, 2022, to July 15, 2022. FLIR E8-XT was used to measure 18 times in the first period, 27 times in the second and 30 times in the last period. Figure 7 shows the variation plot for the LT-1T (solid line) and FLIR E8-XT (dotted line). The results show that there are many large gaps between the LT-1T and FLIR E8-XT lines. Table 4 summarizes the performance of the measured values and the average MAE and RMSE are 1.63 and 1.76. The accuracy of the E8-XT meets the device specification within ±2°C.

Table 4. Accuracy of FLIR E8-XT versus LT-1T

Date	Number of measurements by FLIR E8-XT	LT-1T			MAE	RMSE
		Min	Max	Mean		
2022.7.13 ~2022.7.15	18	23.35	26.8	25.8	1.78	1.89
2022.9.27 ~2022.9.29	27	21.48	26.45	24.4	1.82	1.97
2022.10.4 ~2022.10.6	30	21.3	25.8	24.42	1.29	1.42

Comparison of LT-1T, Lepton 3.5 and MLX90614: As shown in Figure 8, leaf temperature was measured three times with LT-1T, Lepton 3.5 and MLX90614 sensors with one leaf from September 22 to October 6, 2022. The Lepton module applied a warm-up time of four minutes after waking up from the sleep mode from calibration. For each Lepton 3.5 and MLX90614 set of measurements, the MAE and RMSE are summarized in Table 5. The minimum, maximum and average leaf temperatures are 21.3, 26.6 and 24.76 degrees. The average MAE and RMSE of the Lepton are 1.47 and 1.51 degrees. The average MAE and RMSE of MLX90614 each being 0.36 and 0.38 degrees. MLX90614

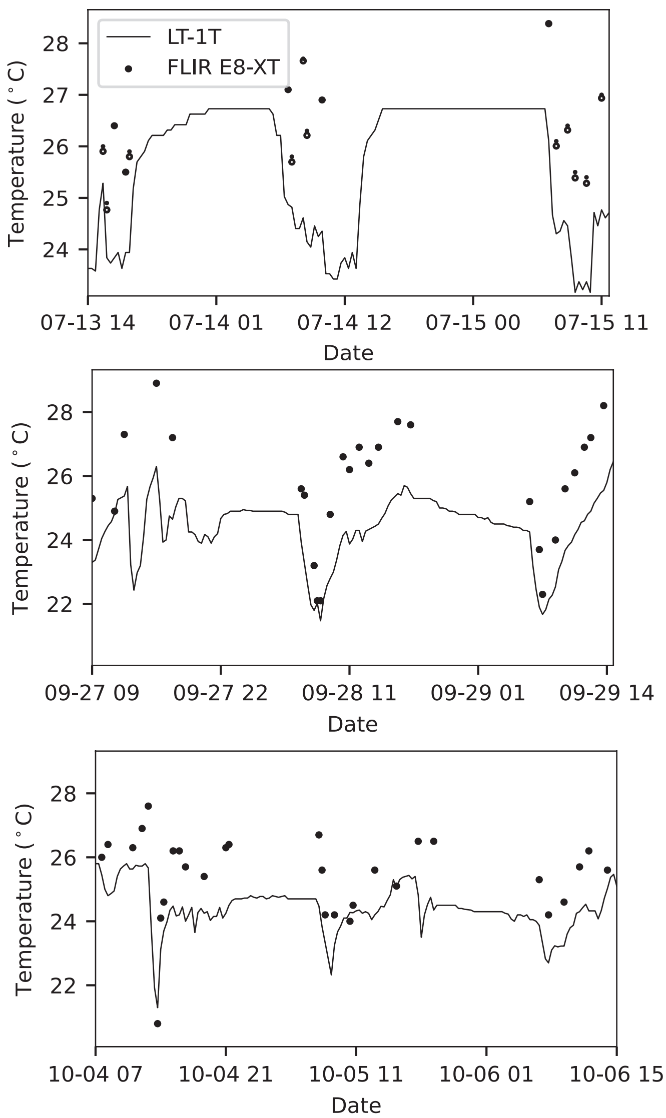

Fig. 7. Comparison of LT-1T and FLIR E8-XT leaf temperature results on each experimental day: (a) July 13–15, 2022, (b) September 27–29, 2022 and (c) October 4–6, 2022.

showed much higher accuracy than the Lepton. Compared to the error values in the device specification, the MLX90614 sensor's error values closely matched the device specification's ±0.5°C. However, the accuracy of Lepton's device specification is ±5°C, but when a module warm-up time of four minutes was applied, the error value dropped down to ±2°C, a better accuracy.

Table 5. Comparison of Lepton 3.5 and MLX90614

Date	LT-1T			Lepton 3.5		MLX90614	
	Min	Max	Mean	MAE	RMSE	MAE	RMSE
2022.9.22 ~2022.9.23	20.65	26.6	25.47	1.83	1.87	0.48	0.49
2022.9.27 ~2022.9.29	21.48	26.45	24.4	1.41	1.45	0.24	0.28
2022.10.4 ~2022.10.6	21.3	25.8	24.41	1.17	1.2	0.37	0.38

As expected, the MLX90614's accuracy was much better than the Lepton 3.5 and E8-XT, according to the tolerances of the device specification. The accuracy of the E8-XT was equal to the device specification value; however, the accuracy of the Lepton 3.5 module was far better than the device specification. The Lepton 3.5 camera, which can be made for less than USD $500, showed similar accuracy to the FLIR E8-XT handheld thermal imager

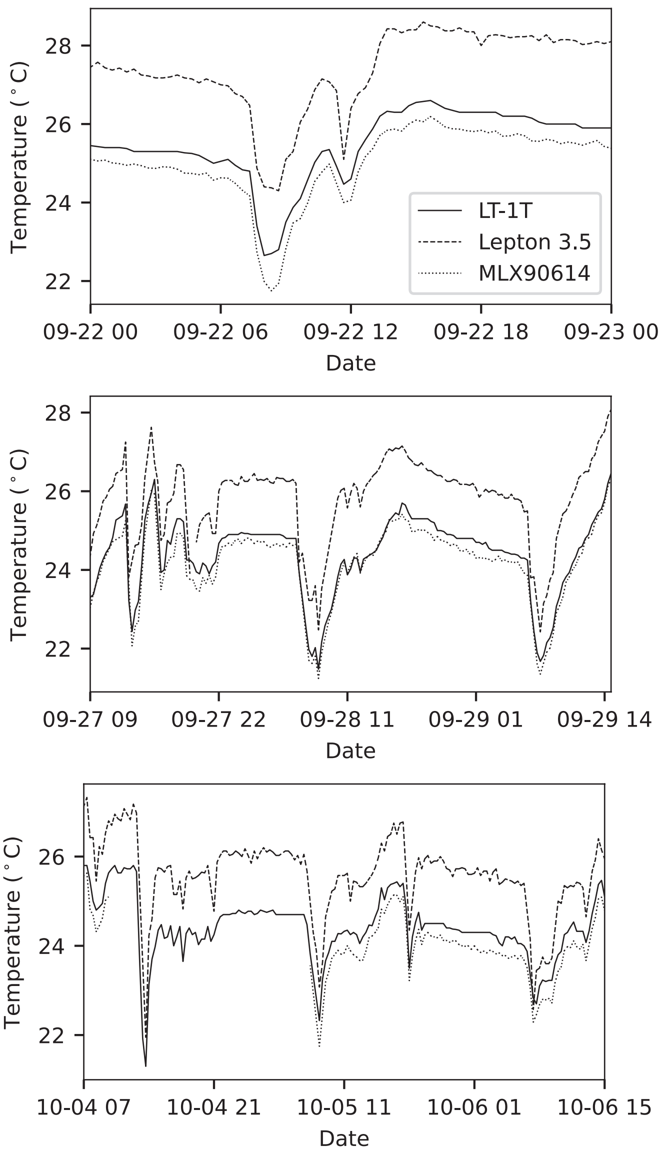

Fig. 8. Comparison of the leaf temperature results from LT-1T, Lepton 3.5 and MLX90614 on each experimental day: (a) September 22–23, 2022, (b) September 27–29, 2022 and (c) October 4–6, 2022.

which is more than US$4,000. Above all, it has the advantage of being able to measure leaf temperature in a fixed position.

This study aims to investigate the feasibility of using a lower-cost Lepton 3.5 thermal imaging camera for measuring crop canopy temperature. This is conducted by comparing its accuracy with other sensors. The study emphasizes the importance of having a calibrated low-cost thermal imaging camera that can offer same accuracy as an intermediate thermal imager, for measuring canopy temperature for researchers. The study results are valuable for researchers looking for a cost-effective solution for monitoring crop water stress, while keeping a similar accuracy.

The feasibility of a periodical and adequate measurement of leaf temperature, using a low-cost Lepton 3.5 thermal imager, was studied. For performance evaluation, temperature readings from the Lepton were compared with those from the LT-1T thermistor, which has the highest accuracy, as well as two other devices: the FLIR E8-XT handheld thermal imaging camera and the MLX90614 infrared sensor. The experiment was conducted three times over the given period on laboratory plants, with a four-minute warm-up time applied for calibration after waking the Lepton from sleep mode. The temperature of a specific leaf was measured every five minutes and was stored on a private server. The accuracy of the measurements was then compared using MAE and RMSE values. The results showed that the MLX90614 sensor had the highest accuracy. However, the Lepton 3.5 module had an accuracy of less than ±2°C, which was similar to FLIR E8-XT and much better than the error value specified for the Lepton. Moreover, the Lepton is a more affordable option, as it can be built with a budget under US$500, while the FLIR E8-XT costs around US$4,000. Thus, it has the advantage of being able to take periodic pictures by being installed as a fixed-type camera.

Conflict of Interest: The authors have no conflicting financial or other interests.

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