



IoT Based Root Stress Detection for Lettuce Culture Using Infrared Leaf Temperature Sensor and Light Intensity Sensor

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Abstract

Root stress is a big problem for lettuce farming in tropical climates, especially temperature root stress. Black root rot, a final stage of the temperature root stress, leads to huge production loss. This paper presents the IoTs based root stress detection system for lettuce cultures. The proposed detection algorithm is based on the leaf energy balance and transpiration patterns. Unlike image sensors based detection methods, leaf energy balance principle and transpiration patterns measured from a lettuce leaf are considered as the key features to address the lettuce root stress conditions. The challenge of detecting lettuce stress by using a leaf sensor is to estimate the non-linear function of stomatal conductance. This paper has clarified the concept of detecting lettuce root stress using the transpiration patterns as well. Graphically, the combination of infrared temperature and light intensity sensors is appropriate to deal with the lettuce root stress detection. The proposed detection algorithm has been designed to detect three conditions of root stress problems: normal, root stress, and black root rot conditions. The infrared sensors are very suitable for the sensitive leaf like lettuce. To evaluate the proposed leaf sensor, the experiments are set up to show that the proposed detection algorithm can accurately detect the temperature root stress in different conditions. Moreover, the detection algorithm based leaf area index (LAI) has been discussed to the proposed detection algorithm. In addition, the performance of the proposed detection algorithm has been compared to the LAI based algorithm. The detection accuracy of the proposed detection method is 95% with different root stress conditions.

Keywords Internet of Things · Precision farming · Leaf sensors · Root stress detection

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1 Introduction

With global hunger on the rise again, the food and agricultural organization of the United Nations (FAO) has issued a sobering forecast on world food production. If global population reaches 9.1 billion by 2050, the FAO says that world food production will need to rise by 70%, and food production in the developing world will need to double [1].

To increase the world food production, the agriculture need to be improved the productivity. Especially, the countries located near the earth equator are appropriate to be considered because sunlight at this area is sufficient for making food twelve months a year. According to the lettuce cultures, the farmer can harvest the lettuce for 12 crops. However agriculture in tropical countries is unavoidable to face the strong net radiation caused by the sunlight. The precision sensor solution including the Internet of Things (IoT) is very suitable to be the key of success for modern agricultures.

Precision farming is very important to help the farmer to realize the high quality productivity. Sensor technologies are the best solutions to do this. According to the root stress problem caused by the high temperature root stress, there are two groups of leaf sensor methods: external change based methods and internal change based methods.

Currently, there are various image sensor solutions to realize the precision farming. According to leaf sensor based image solutions, this solution can analyze the plant stress effectively. In 2011, Seelye et al. [2] developed low cost colour sensors for monitoring leaf colour of plant tissues growing in a modified micropropagation. In 2017, Thorat et al. [3] introduced an IoT based smart image sensor for leaf disease detection.

In 2018, Okamoto et al. developed plant growth estimation technologies by image analysis based on visible and thermography thermal images captured by cameras in real time and non-destructive leaf and root growth in lettuce hydroponic culture. The study shows that there is a correlation between the leaf area of the lettuce actually harvested and the area length of the root [4].

As discussed above, the image sensor solutions are considered as the external change solutions. These methods rely on the image information 2D or 3D information to analyze the plant stress. The image sensor solution is suitable for the stress that can analyze the leaf external information like leaf color, leaf area index (LAI), and leaf emotion and so on. The limitation of using the leaf external information is when these applies to analyze the root stress situation caused by high temperature root stress, the detection accuracy would be significantly decrease because the external change is so rough compared to plant transpiration and leaf temperature change. Thus internal change based leaf sensor methods have been introduced to be the best solutions for detecting and analyzing the plant stress caused by the internal change like root stress.

To detect the plant water status, a microwave method was introduced in 2006 as a novel method. The microwave sensor has been developed for precisely detecting plant water status or diagnosing water stress in plants. It is based on a microwave sensor, which contains a resonant cavity. Comparing to the methods introduced previously this method detects the plant water status more directly. It does not need a fusion sensor to measure more than one parameter to determine the plant water status. So it is more convenient and accurate than other methods. In 2016, an alternative solution of leaf sensor based on microwave sensor was presented by E. Pievanelli et al. The leaf wetness sensor is realized connecting the horn antenna to two transceivers by a 3-port circulator. Measuring the ratio between transmitted and received signal is possible to evaluate the reflector coefficients and consequently the wetness [5, 6].

Recently, remote sensing technologies have been presented for large area precision agricultures. Leaf area index (LAI) and leaf temperature have been introduced as the important biophysical parameters for estimating gas exchange, crop yields, and root stress for the precision agricultures.

Leaf area index (LAI) is an important vegetation biophysical parameter to estimate gas-vegetation exchange process. The airborne discrete-return light detection (LiDAR) based solution can estimate the LAI of low-stature vegetation, such as the maize [11]. However, the achievement of this technique has to complete with Beer-Lambert law and the alometric relationship. Thus, the LiDAR offers the possibility to characterize the 3-D variation of LAD over space [12]. In addition, the problem of LAI is that the saturation is possible to occur in the nadir direction, and vary with crop canopy structure and view zenith angles. To overcome this issue, the multi-angular remote sensing was presented to improve the monitoring accuracy and stability of VIs [13].

In 2017, Jin et al. developed a theoretical model based on physical energy balance equations and remote sensing data to evaluate heavy-metal stress in rice. Canopy temperature and LAI were used as the useful features to detect the heavy metal stress. Three extreme states of heavy-metal stress in rice were analyzed to be three states [7]. The hyperspectral based remote sensing method has been introduced for identifying of pathogen discrimination in coffee plants [14]. In [15], the simplified version of the boundary leaf resistance was presented to reduce the thickness of leaf lamina boundary layer so that the parasite population is rare filed.

Besides the remote sensing applications, the difference of leaf and air temperatures has been considered as the biophysical parameter for wireless sensor network (WSN) applications. In 2018, Daskalakis et al. develop the leaf sensor which used for the first time ambient backscattering over analog modulated (FM) signals. The leaf sensor is based on an ultra-low power microcontroller. Ambient backscattering has the potential to be the next new primitive approach for extremely low power communication [8].

The chlorophyll fluorescence (ChF) detection methods have been presented to be suitable for detecting the plant stress as an internal change principle. The principle of ChF method is very useful for detecting leaf stress especially nutrient stress and abiotic stress. The limitation of ChF method is that some techniques need the dark environment to analyze the plant stress. This is suitable as an alternative method [9, 10].

This paper presents the IoTs based root stress detection system for lettuce cultures. The proposed detection algorithm is based on the leaf energy balance principle and transpiration patterns. Unlike image sensors based detection methods, transpiration patterns derived from a lettuce leaf are considered as the key features to address the lettuce root stress conditions. The challenge of detecting lettuce stress by using a leaf sensor is to estimate the non-linear function of stomatal conductance. This paper has clarified the concept of detecting lettuce root stress using the transpiration patterns as well.

2 Materials and Methods

As discussed in the literatures, this section explains the details of the leaf sensor development. The concept of development starts with the overall precision detection system. Figure 1 shows the overall system of the IoT based root stress detection. In order to early detect the lettuce root health in real-time, the system consists of four parts (1) people, (2) cloud, (3) lettuce culture and (4) sensors. Lettuce is one kind of vegetable that consumes low levels of fertilizer. Its leaf

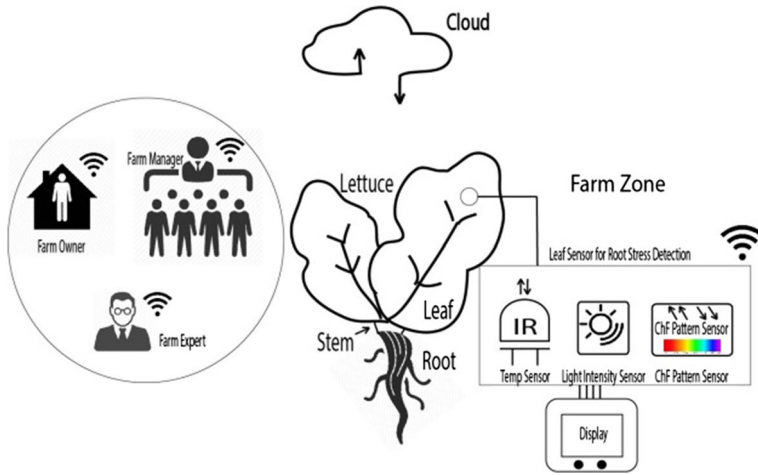


Fig. 1 Schematic diagram of Internet of Things (IoTs) based temperature root stress detection using a leaf sensor. The leaf sensor consists of temperature sensor, and light intensity sensor. A farm owner, a manager, and an expert can real-time monitor the temperature root stress situation

thickness is not largely. Thus leaf sensors need to design as an infrared leaf sensor. We cannot attach any kind of disguised material to the leaf. Otherwise our sensors would be major cause of lettuce stress.

The sensor module as shown in Fig. 1 consists of internal change based sensor like infrared temperature sensor. Light intensity sensor is used to analyze the relationship among the heat radiation, internal change in lettuce plant and light intensity. The ChF sensor is an optional sensor to be a second opinion sensor for analyzing the other kinds of lettuce stress.

The communication of each module can be realized by WiFi connection via cloud platform.

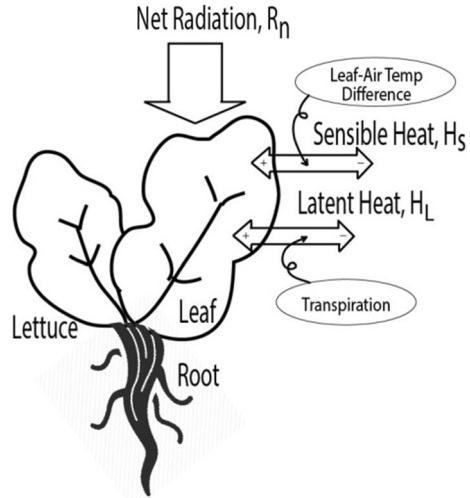
2.1 The Concept of the Root Stress Detection by the Leaf Sensor

The principle of the proposed leaf sensor is based on energy balance principle as shown in Fig. 2. The net radiation R_n is balanced by sensible heat H and latent heat λE as expressed in Eq. (1). In Eq. (2), Q_a is the radiative forcing, defined as the sum of absorbed solar radiation and incident longwave radiation. Longwave radiation is emitted by the leaf in proportion to its temperature (T_{leaf} , °C) raised to the fourth power. Sensible heat is exchanged between the leaf and air temperature (T_{air} , °C) in proportion to the temperature difference divided by a diffusion resistance (r_H , sm^{-1}). Similarly, latent heat is exchanged in relation to the vapor pressure deficit (VPD) between the leaf and the surrounding air divided by a diffusion resistance (r_w , sm^{-1}) [16].

$$R_n = H + \lambda E \tag{1}$$

$$Q_a = \epsilon\sigma(T_s + 273.15)^4 + \rho C_p \frac{(T_{leaf} - T_a)}{r_H} + \frac{M_w \lambda}{R(273 + T_a)} \cdot \frac{e_s(T_{leaf}) - e_a(T_a)}{r_w} \tag{2}$$

Fig. 2 Schematic diagram of a lettuce when the net radiation is balanced by sensible heat and latent heat



The transpiration rate depends on the total resistance r_w (actually the sum of the stoma resistance and the boundary layer resistance) as expressed in Eq. (3). In Eq. (4), Vapor pressure deficit (VPD) can be calculated by the leaf temperature, the air temperature, and relative humidity RH [17]. The transpiration E can be expressed in function of VPD, and stomatal conductance g_{sw} as in Eqs. (5) and (6).

$$\lambda E = \frac{M_w \lambda}{R(273 + T_a)} \cdot \frac{e_s(T_{leaf}) - e_a(T_{air})}{r_w} \tag{3}$$

$$VPD = (610.7) \cdot \left[10^{\left(\frac{7.5T_{leaf}}{237.3 + T_{leaf}} \right)} - \left(\frac{RH}{100} \right) \cdot 10^{\left(\frac{7.5T_{air}}{237.3 + T_{air}} \right)} \right] \tag{4}$$

$$E = [VPD/BP] * g_{sw} \tag{5}$$

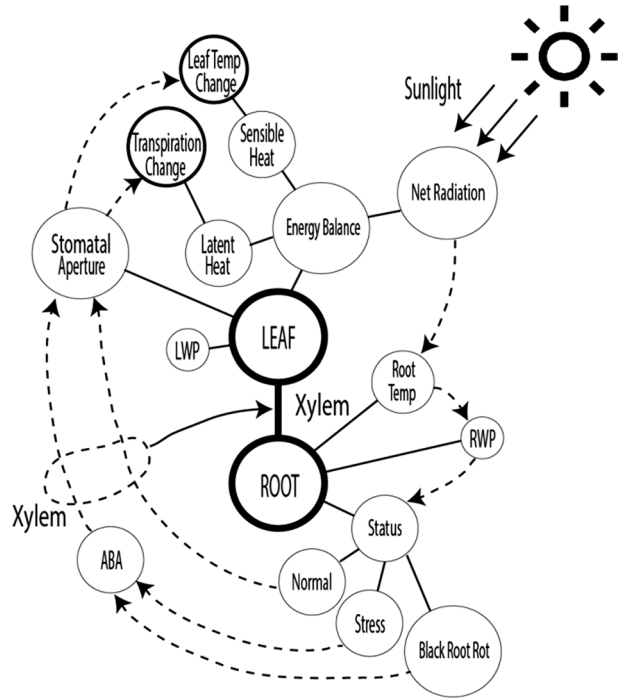
where g_{sw} is the stomatal conductance, BP is the barometric pressure in kPa (101.3 at sea level).

$$E = f(T_{leaf}, T_{air}, RH, g_{sw}) \tag{6}$$

Since stomatal conductance g_{sw} in Eq. (6) is a non-linear function, transpiration E is so difficult to determine the exact values, especially during plant stress. When a lettuce faces to temperature root stress caused by high net radiation, abscisic acid (ABA) hormones are generated and mixed into the water and nutrient via xylem as shown in Fig. 3. The ABA hormones affecting to the change of stomatal conductance, thus the latent heat decrease as well [18, 19]. Moreover, the change of stomatal conductance caused by the temperature root stress affects to the decrease of the latent heat according to Eq. (3). Thus the difference of leaf and air temperature DT_{LA} , VPD, and E would also significantly change as well.

Figure 4 shows the patterns of transpiration and the difference of leaf and air temperature, DT_{LA} . DT_{LA} is the key features of the proposed leaf sensor to detect the root stress. In

Fig. 3 The concept of stomatal aperture changes caused by the net radiation when considering the leaf energy balance and abscisic acid (ABA) with three conditions of temperature root stress: normal, root stress, and black root rot



addition, the patterns of transpiration rate in different conditions of lettuce root would be a main feature for early detecting the root stress.

During the normal condition (no root stress), the transpiration patterns, DT_{LA} , and the lettuce image are shown in Fig. 4a–c, respectively. When the lettuce faces to root stress, the transpiration patterns, DT_{LA} patterns, and the lettuce image become the line (b) in Fig. 4a, b, respectively. The lettuce image during root stress is shown in Fig. 4d. The black root rot situation, final stage of root stress, the transpiration pattern and DT_{LA} become the line (c) as shown in Fig. 4a, b, respectively. The lettuce image with black root rot damaged by temperature root stress caused by high net radiation is shown in Fig. 4e. This is impossible to compensate back to the normal condition or even the stress condition.

2.2 The Detection Algorithm

After clarifying the concept of stress detection, the detection algorithm would be explained in this section. According to Eq. (6), the difference of leaf and air temperatures DT_{LA} , light intensity L_X , are used to be the inputs of the proposed detection algorithm. The L_{XA} and L_{XB} related to the saturated transpiration of green oak lettuce for tropical climates. In this paper, the L_{XA} and L_{XB} are set to be 20,000 lux and 73,000 lux, respectively [20]. The basic concept of the detection algorithm is to divide the patterns into three regions related to the amount of the net radiation. The light intensity L_X is thresholded by L_{XA} and L_{XB} values as shown in Fig. 5b. Thus, there are three regions to be considered, R1, R2, and R3 as shown in Fig. 5c, d. These regions would be represented the region area of each part related to the different levels of net radiation. R1 is

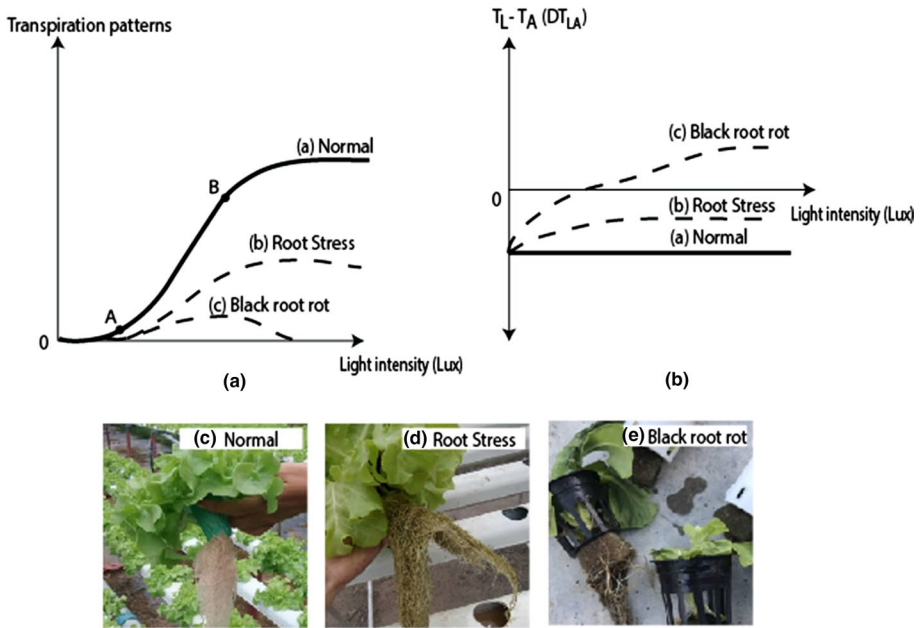


Fig. 4 Transpiration patterns of green oak lettuce **a** transpiration patterns in different stress conditions, **b** the difference of leaf temperature and air temperature (DT_{LA}) in different stress conditions, **c** a green oak with root stress, **d** green oak with temperature root stress and **e** green oak with black root rot

the region that the light intensity L_X gradually increases. The latent heat and transpiration rate would also increase. When a lettuce is healthy (no temperature root stress), g_{sW} has no effect of ABA. Thus DT_{LA} is the negative value. When L_X is beyond L_{XB} , the decrease of g_{sW} and E depends on the conditions of stress according to Fig. 4b. The change of g_{sW} caused by ABA hormones affecting to the change of latent heat, transpiration patterns, and DT_{LA} inevitably. Figure 5a shows the flowchart of the detection algorithm. There are four steps (steps 1–4) of DT_{LA} determination. The decision making is based on DT_{LA} patterns according to Fig. 5e.

2.3 Sensor Implementation

The concept of the leaf sensor that can be able to detect the root stress is shown in Fig. 6. The infrared temperature sensor and the controller would be in the bottom side of the leaf sensor. The light intensity sensor and the display are on the top-side of the leaf sensor. In case of long time monitoring, the solar panel, battery charger and battery are employed as the DC power supply for the sensor system.

To realize the proposed concept for internal change detection, the concept of leaf sensor has been designed as shown in Fig. 7. Figure 7a is the tested circuit of IoT based leaf sensor. The prototype of the proposed leaf sensor is shown in Fig. 7b and 7c, respectively.

As shown in Fig. 7a, b, the prototype of leaf sensor has been designed with OLED display. Thus a user can use it as a portable sensor without WiFi connection to manually detect the lettuce root stress in field test as well. The lists of hardware components and software are shown in Tables 1 and 2, respectively.

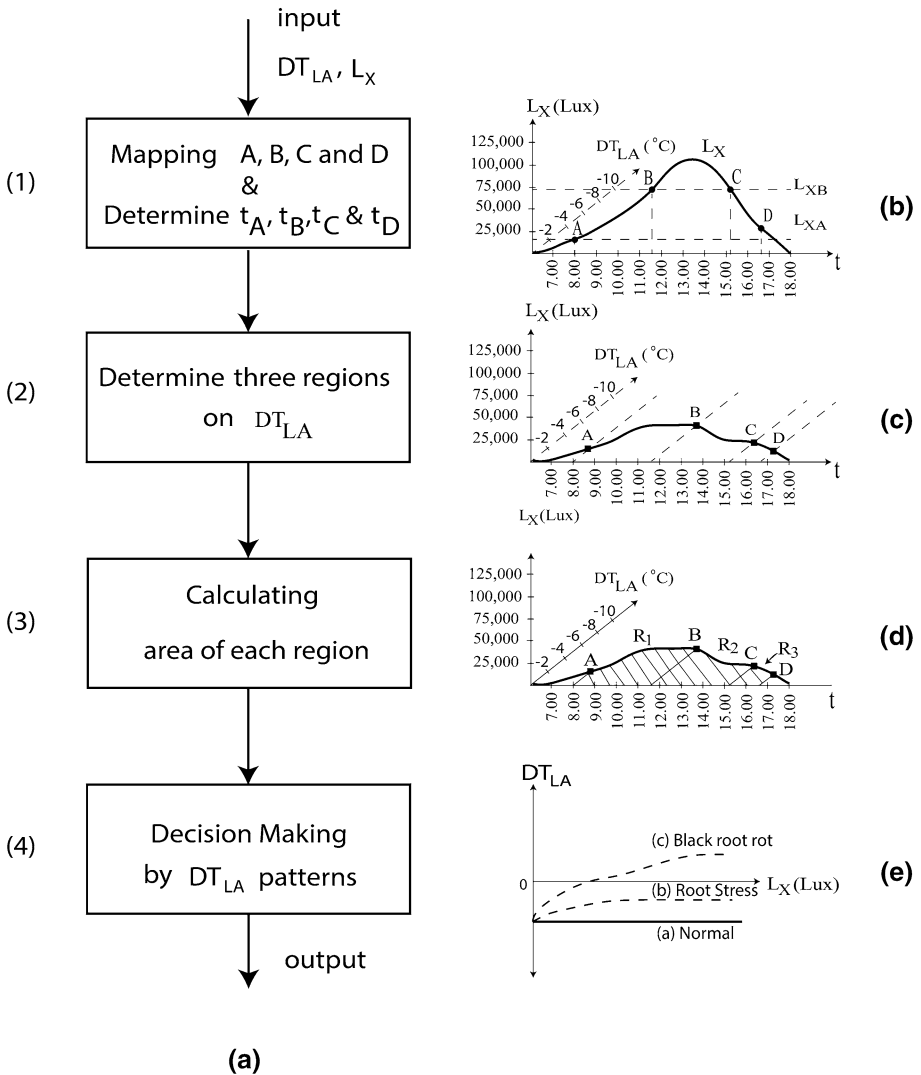


Fig. 5 The proposed detection algorithm **a** the block diagram of the algorithm consists of four steps, **b** thresholding L_X by L_{XA} and L_{XB} , **c** region determination of DT_{LA} , **d** calculating area of each region, and **e** decision making by DT_{LA} patterns

3 Experimental Results

To evaluate the proposed root stress detection system, the experiments are set up to measure the difference of leaf temperature T_L and air temperature T_A at root temperature 30 °C, 40 °C, 50 °C and 60 °C. The ambient temperature is controlled to be between 28 °C and 32 °C. As discussed previously, the internal change of lettuce leaf would be able to detect with the proposed detection system. In Sect. 3.1, the difference of T_L and T_A vs light intensity (lux) are shown.

Fig. 6 The proposed leaf sensor for measuring leaf temperature, air temperature, and light intensity. Display, controller based WiFi communication, and solar panel with a 12 V-battery and a battery charger are included in the system as well

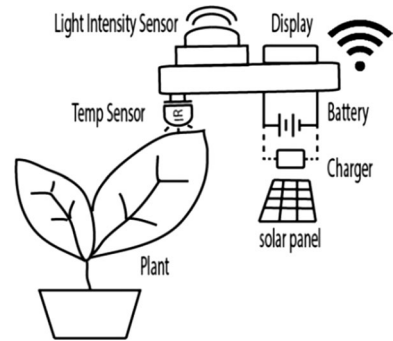
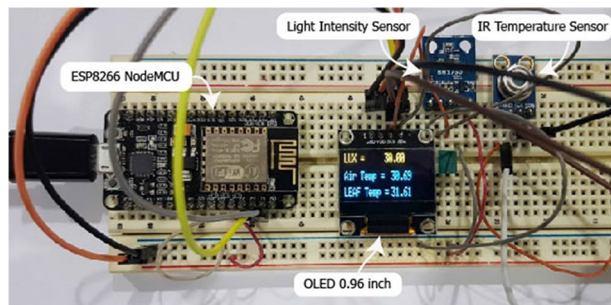


Fig. 7 The prototype of the proposed leaf sensor. **a** The tested circuit of the proposed leaf sensor, **b** top view of the proposed leaf sensor, and **c** bottom view of the leaf sensor



(a)



(b)



(c)

Table 1 List of hardware components for sensor implementation

Hardware	Details	
Controller	ESP8266	Arduino controller with WiFi communication feature
Light sensor	BH1750	Light sensor for measuring light intensity (lux)
Infrared temperature sensor	MLX90614	Precision infrared object temperature and ambient temperature (degree Celcius) sensor
OLED display	0.96 inch	Organic LED display 0.96 inch
Solar panel	10 wattage	Power supply module
12 V DC charger	20 wattage	Power charging module

Table 2 List of software for sensor implementation

Software	Details
Arduino IDE	Programing ESP8266 Node MCU to deal with sensor
Cloud platform	https://Thingspeak.com

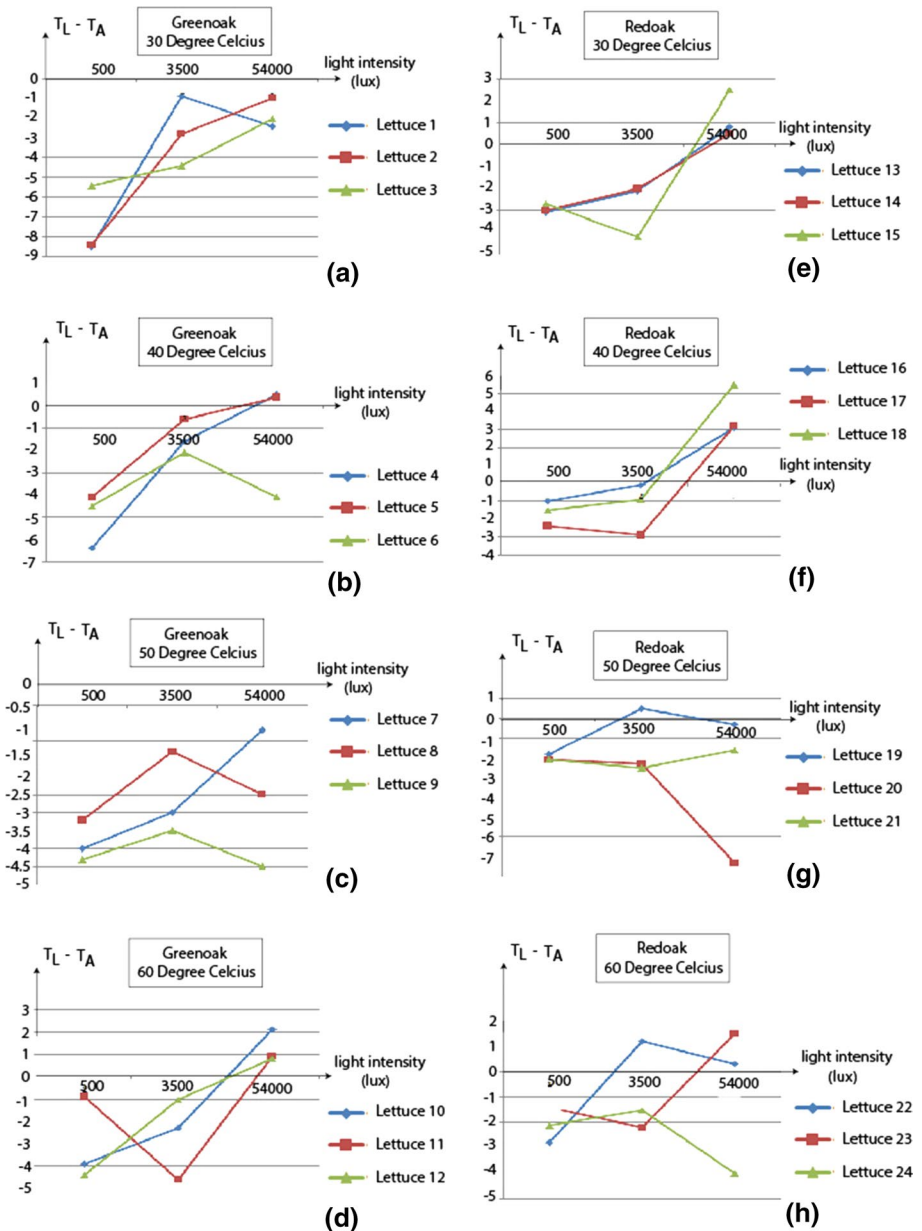


Fig. 8 The experimental results of the proposed leaf sensors

Table 3 Experimental results: difference of T_L and T_A with 500 lux of light intensity when root temperature varies between 30 and 60 °C

No	Lettuce type	Root temp (°C)	Light intensity = 500 lux		
			T_L (°C)	T_A (°C)	$T_L - T_A$ (°C)
1	Green oak	30	22.1	30.6	-8.5
2	Green oak	30	21.3	29.7	-8.4
3	Green oak	30	23.9	29.3	-5.4
4	Read oak	30	25.5	28.6	-3.1
5	Red oak	30	25.6	28.6	-3
6	Red oak	30	25.9	28.6	-2.7
7	Green oak	40	23.3	29.7	-6.4
8	Green oak	40	25.3	29.4	-4.1
9	Green oak	40	24.8	29.3	-4.5
10	Red oak	40	27.8	28.8	-1
11	Red oak	40	26.3	28.7	-2.4
12	Red oak	40	27.2	28.7	-1.5
13	Green oak	50	27.4	31.4	-4
14	Green oak	50	27.6	30.8	-3.2
15	Green oak	50	26.2	30.5	-4.3
16	Red oak	50	28.4	30.2	-1.8
17	Red oak	50	28.01	30.09	-2.08
18	Red oak	50	27.8	29.9	-2.1
19	Green oak	60	27.3	31.2	-3.9
20	Green oak	60	30.1	31	-0.9
21	Green oak	60	27.5	31.9	-4.4
22	Red oak	60	28.1	30.9	-2.8
23	Red oak	60	29.6	31	-1.4
24	Red oak	60	28.8	30.9	-2.1

To realize the performance of the proposed root stress detection system, the samples of 24 hydroponic lettuces have been tested in different root temperatures. The weight per plant of green oak and red oak is 1.2 g and 1.0 g respectively. The reason of selecting the hydroponic lettuce is easy to evaluate lettuce root health. Root color based method is the alternative way to evaluate the temperature root stress conditions. The clear white, light brown and black represent no stress, temperature root stress, and black root rot, respectively. However the proposed detection methods can be applied to both organic and hydroponic cultures.

3.1 Difference of T_L and T_A (DT_{LA}) Versus Light Intensity

The objective of this experiment is to show that the difference of leaf temperature T_L and ambient temperature T_A can be determined by using the proposed detection system. The T_L

Table 4 Experimental results: difference of T_L and T_A with 3,500 lux of light intensity when root temperature varies between 30 and 60 °C

No	Lettuce type	Root temp (°C)	Light intensity = 3500 lux		
			T_L (°C)	T_A (°C)	$T_L - T_A$ (°C)
1	Green oak	30	29.5	30.4	-0.9
2	Green oak	30	28.4	31.2	-2.8
3	Green oak	30	27.3	31.7	-4.4
4	Red oak	30	29.8	31.9	-2.1
5	Red oak	30	29.9	31.9	-2
6	Red oak	30	27.7	31.9	-4.2
7	Green oak	40	29.2	30.8	-1.6
8	Green oak	40	30.8	31.4	-0.6
9	Green oak	40	29.5	31.6	-2.1
10	Red oak	40	31.8	31.9	-0.1
11	Red oak	40	29.3	32.2	-2.9
12	Red oak	40	31.6	32.5	-0.9
13	Green oak	50	28.3	31.3	-3
14	Green oak	50	30.3	31.6	-1.3
15	Green oak	50	28.1	31.6	-3.5
16	Red oak	50	32.2	31.7	0.5
17	Red oak	50	29.8	32.1	-2.3
18	Red oak	50	29.8	32.3	-2.5
19	Green oak	60	28.7	31	-2.3
20	Green oak	60	26.4	31	-4.6
21	Green oak	60	30.4	31.4	-1
22	Red oak	60	33.1	31.9	1.2
23	Red oak	60	29.9	32.1	-2.2
24	Red oak	60	30.8	32.3	-1.5

and T_A in different root stress conditions are compared to light intensity. The experimental results show that the internal changes in difference of T_L and T_A relate to the heat radiation affecting by sunlight. The representative of the heat radiation from sunlight is measured by using the light intensity sensor (lux).

According to Fig. 8, Fig. 8a–d is the experimental results of green oak. When the root temperature increases, the different trends of T_L and T_A are higher (more positive). Figure 8e–h is the experimental results of red oak. Noticed that red oak is more sensitive than green oak comparing to the same level of root temperature. Tables 3, 4 and 5 shows experimental data used to plot Fig. 8.

3.2 The Comparison Between the Proposed Detection and the LAI Method

In order to evaluate the detection performance of the proposed detection system, the internal change detection and the external change detection would be explained in more details. Figure 9 shows the comparison of the internal change and external change. When the root temperature is at 60 °C, the difference of T_L and T_A (DT_{LA}) has been significantly changed in different light intensity 500 lux, 3500 lux and 54,000 lux. This means that the lettuce

Table 5 Experimental results: difference of T_L and T_A with 54,000 lux of light intensity when root temperature varies between 30–60 °C

No	Lettuce type	Root temp (°C)	Light Intensity = 54,000 lux		
			T_L (°C)	T_A (°C)	$T_L - T_A$ (°C)
1	Green oak	30	30.9	33.3	-2.4
2	Green oak	30	32.8	33.8	-1
3	Green oak	30	32.01	34.03	-2.02
4	Red oak	30	35.5	34.7	0.8
5	Red oak	30	35.6	35.1	0.5
6	Red oak	30	38.2	35.7	2.5
7	Green oak	40	33.8	33.3	0.5
8	Green oak	40	34.2	33.8	0.4
9	Green oak	40	31.2	35.3	-4.1
10	Red oak	40	39.2	36.1	3.1
11	Red oak	40	39.3	36.1	3.2
12	Red oak	40	41.9	36.4	5.5
13	Green oak	50	33.8	34.5	-0.7
14	Green oak	50	32.01	34.5	-2.49
15	Green oak	50	30.4	34.9	-4.5
16	Red oak	50	34.8	35.1	-0.3
17	Red oak	50	28	35.3	-7.3
18	Red oak	50	34.1	35.7	-1.6
19	Green oak	60	37.4	35.3	2.1
20	Green oak	60	35.5	34.6	0.9
21	Green oak	60	36.6	35.8	0.8
22	Red oak	60	36.2	35.9	0.3
23	Red oak	60	37.6	36.1	1.5
24	Red oak	60	32.6	36.6	-4

root was affected by the temperature root stress. According to the external change feature, the red oak leaf was still fresh except two leaves in the dash circle that gradually started to wilt. Thus the external change features are more difficult to implement the early stage detection of lettuce root stress.

Figure 10 shows the experimental results of LAI based detection method with green oak by using Easy Leaf Area application for a smartphone. The LAI value of no stress green oak is 174.24 cm² as shown in Fig. 10a. After facing temperature root stress at 55 °C, the LAI value of green oak significantly reduces by 20% (141.96 cm²), approximately. Table 6 shows the results of the LAI tests with 20 lettuces of green oak. The response detection time of the proposed method and the LAI method are 5 min and less than 60 s, respectively.

In practical, the response time of the detection system considerably affects to losing of crop yields. The response time of LAI method is equal to 5 min, approximately. This is not sufficient to early detect the temperature root stress. On the other side, the response time of the proposed detection system is less than 30 s. This is sufficient to early detect the temperature root stress for compensation in real-time.

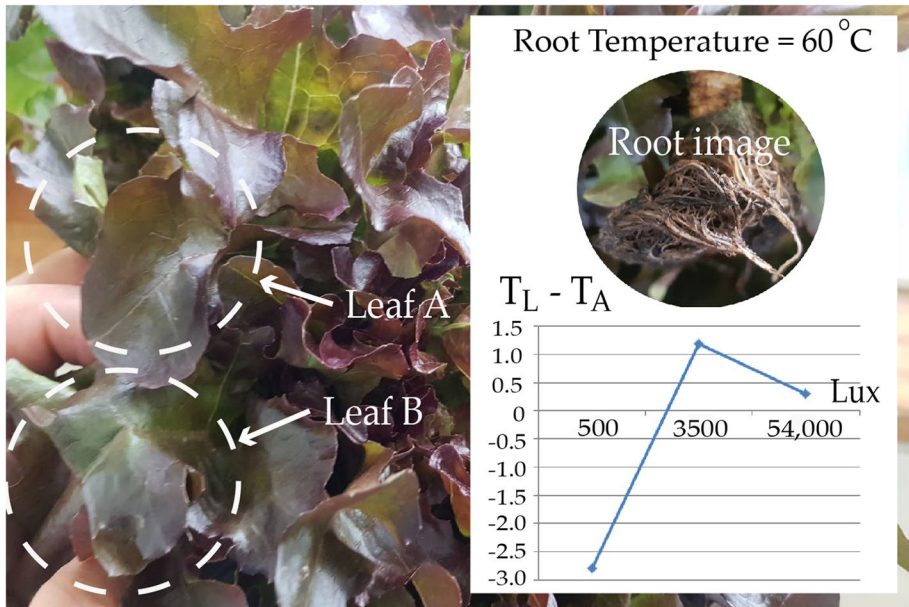


Fig. 9 The internal change detection and the external change detection red oak with 60 °C of root temperature

4 Discussion

According to the experimental results, the difference of T_L and T_A in case of green oak and red oak in root temperature at 30 °C is very interested. Basically, the requirement of red oak in term of light intensity (lux) is lower than green oak. Normally, light intensity for green oak lettuce cultures is around 40,000–70,000 lux. The red oak cultures need only 30,000–50,000 lux approximately. This is the reason that red oak is more sensitive than green oak in term of root temperature increase. The comparison between green oak and red oak in term of root temperature is shown in Table 7. Figure 11 shows the internal change of red oak and green oak.

Figure 12 shows the detection error of the proposed root stress detection system. Basically, when the root temperature is at 60 °C, the difference of T_L and T_A should be close to zero or positive. In this case the difference of T_L and T_A is -7.5 . This is because of the limitation of the proposed detection system cannot effectively detect the leaf temperature when the leaf is wet. In practical, the lettuce cultures in tropical climate areas would compensate relative humidity RH by using foggy system. However, the foggy pressure and duration are recommended to be lower than 70% of RH. The measurement position of infrared temperature sensor should select a leaf in the vertical direction to avoid the dropped water on the leaf.

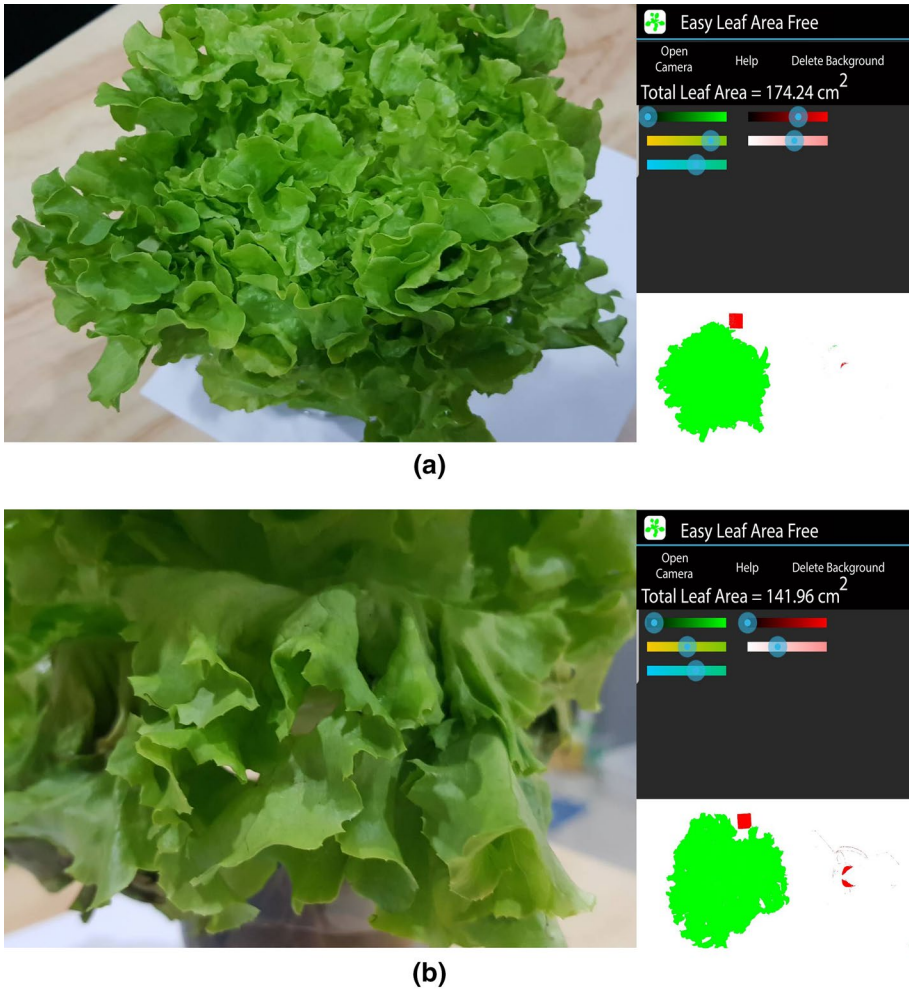


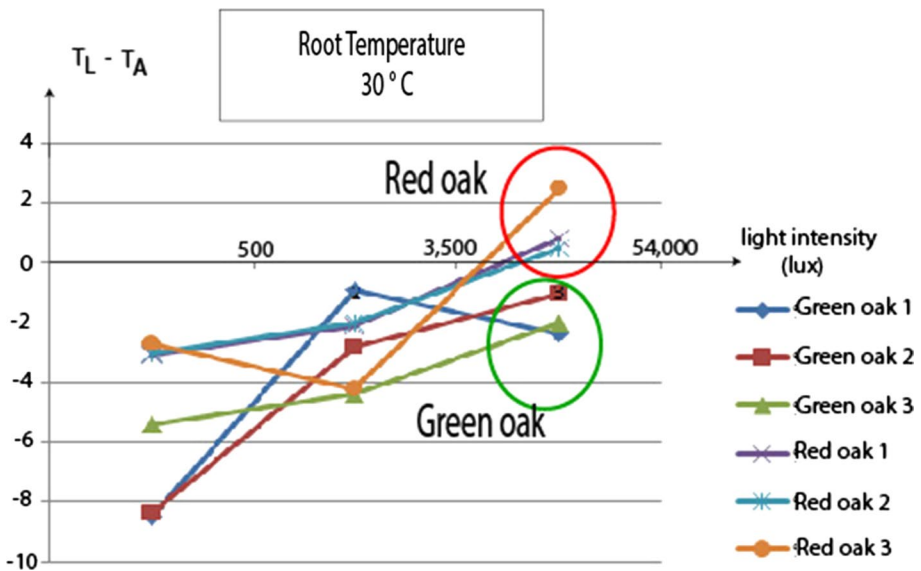
Fig. 10 Experimental Results of LAI based detection method with green oak by using easy leaf area for a smartphone. **a** Green oak with no root stress, **b** green oak with black root rot (final stage of root stress).

Table 6 The experimental results of black root rot stress detection

Details	The LAI algorithm	The proposed algorithm
Accuracy (%)	85	95
Response time	5 min	< 60 s

Table 7 Comparison between green oak and red oak when root temperature is 30 °C and the light intensity at 500 lux, 3,500 lux and 54,000 lux

No	Lettuce type	Root temp	Light Intensity	Light Intensity	Light Intensity
			500 lux	3500 lux	54,000 lux
			$T_L - T_A$ (°C)	$T_L - T_A$ (°C)	$T_L - T_A$ (°C)
1	Green oak	30	-8.5	-0.9	-2.4
2	Green oak	30	-8.4	-2.8	-1
3	Green oak	30	-5.4	-4.4	-2.02
4	Red oak	30	-3.1	-2.1	0.8
5	Red oak	30	-3	-2	0.5
6	Red oak	30	-2.7	-4.2	2.5

**Fig. 11** The comparison of the internal change results of green oak and red oak with the same root temperature level (30 °C). The red oak (red circle) is more sensitive to temperature root stress than the green oak (green circle). (Color figure online)

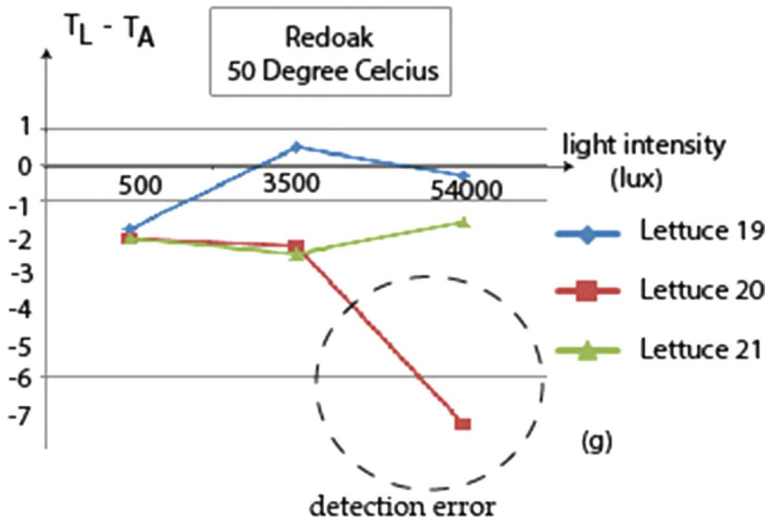


Fig. 12 Detection error of the proposed detection system

5 Conclusion

This paper presents the root stress detection system based on internal change detection using a novel leaf sensor system. The energy balance principle, stomatal conductance and lettuce leaf transpiration in different light intensity conditions are considered as the internal change features for detecting the lettuce root stress. The real-time detection system realized by IoT based controller has been implemented to monitor the internal change of lettuce culture. The experimental results show that the real-time monitoring of the T_L and T_A in different light intensity condition leads to effective detection for the lettuce root stress situation affected by root temperature increased. Moreover the internal change based root stress detection can be applied to different types of lettuce.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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