A Review on Leaf Temperature Sensor: Measurement Methods and Application

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Abstract. Leaf temperature is the guarantee for the plant to carry out the life activities and closely related to plants' healthy growth and crops' planting management. The accurate measurement of leaf temperature is significant to understand the physiological condition, guide farmland irrigation, select variety and forecast production, etc. The development of plant leaf temperature measurement and requirements of application in recent years at home and abroad were briefly summarized and reviewed in the paper. Firstly, the status of application research and achievements of leaf temperature were introduced from the methods of measurement and scientific experiments. Then it analyzed and compared the principle, advantages and disadvantages and measurement of several common methods in detail including thermal resistance measurement, thermocouple measurement, infrared temperature measurement, infrared thermal imaging measurement and the leaf temperature model. At last, some problems urgently needed to be solved and the development direction of the field were presented, which could provide a reference for the further study of the leaf temperature sensor.

Keywords: Leaf temperature · Sensor · Infrared temperature measurement · Infrared thermal imaging · Leaf temperature model

1 Introduction

Plant leaf temperature is the surface temperature of leaf where is exposed in the atmosphere. The leaf temperature is influenced by the physiological structure of plant itself and the meteorological factors such as solar radiation, air temperature and wind. Leaf temperature varies at different times. In the plants and crops planting, it is more and more seriously to request people to accurately measure plant leaf temperature, so we can understand the relationship between the internal energy, physiological status and environmental factors. Studying the changes of leaf temperature is important for the research on field evapotranspiration, irrigation, variety breeding and yield forecasting.

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In 1875, the German E. Askenasy explained the concept of leaf temperature, but because of the backward measure technology, the development of leaf temperature application was slow. To measure leaf temperature, thermal resistance could be used [1]. With the development of the thermocouple technology, the leaf temperature was measured by thermocouple. The leaf temperature was measured with thermocouple to study the winter transpiration of greenhouse cucumber in South China [2]. However, due to directly contacting the leaf, the heat conduction is easy to occur, which makes the big error of measurement. It consumes time and the range of temperature is limited [3]. With the rapid development of infrared technology, scientists began to measure the plant leaf temperature with the infrared radiation thermometer, which realized the non-contacting measurement of leaf temperature. Kalyar et al. [4] measured the leaf temperature and used the characteristics of the leaf gas exchange to induce the heat resistance of sunflower. With the infrared technology becoming mature, the thermal infrared imager was produced and applied in the agricultural gradually. The sorghum leaf temperature was measured by infrared imaging instrument to study the water status of the plants under drought stress [5]. The development of leaf temperature measurement technology laid a solid foundation for people to understand the physiological index of plants and the growth of crops.

Starting from the research on leaf temperature measurement, the experiment status and achievements of leaf temperature sensors' application was described and the significance of leaf temperature measurement was showed by the paper. It is summarized that there are several common measurement methods including thermal resistance measurement, thermocouple measurement, infrared temperature measurement, infrared thermal imaging measurement and leaf temperature model. The characteristics and application of five temperature measurement methods were introduced and the problems and development direction of the leaf temperature measurement were pointed out, which provided a reference for the further research on the leaf temperature sensors.

2 Temperature Measurement Theory and Sensing Requirement

Leaf temperature is the surface temperature of the plant leaf, which affects the photosynthesis and transpiration of plants, and it is used to express the temperature of plant and analyze the physiological activities of plants. The degree of plants' drought or water can be indicated and the growth rate and output of the crops can be affected by leaf temperature. There are a lot of methods for leaf temperature measurement such as thermal resistance temperature measurement, thermocouple temperature measurement, infrared temperature measurement, infrared thermal imaging temperature measurement. In addition, the temperature of plant leaves can be obtained by the leaf temperature model. According to different conditions and measurement requirements, the suitable measurement method can be chosen. In the practical application, there are many specific requirements for the leaf temperature sensor. Firstly, the leaf temperature varies from time to time, and the temperature range should be satisfied with the leaf

temperature sensor. Secondly, the stability should be guaranteed when the leaf temperature sensor measures in the harsh environment, such as humidity, high temperature and other environment. In addition, to obtain the accurate temperature data in the experiment, the influence of external factors on the leaf temperature sensor should be eliminated as large as possible, which can ensure the measurement accuracy.

3 The Status of the Leaf Temperature Sensor in Application Experiment

The leaf temperature is measured by the leaf temperature sensor. At present, the leaf temperature sensor is widely used in the experiment of plants especially crops. The leaf temperature not only affects the physiological and energy changes of the plants, which reflects the health status of plants, but also reflects the water status of crops, which can guide crop irrigation and drought resistant genotype selection. In addition, the output of crops has a close relationship with the leaf temperature. Here will introduce the experiment status of the specific application of leaf temperature sensor in these aspects.

3.1 Application Experiment of the Leaf Temperature Sensor in the Physiological Health of Plants

Leaf temperature can reflect the physiological activity of plants, and the growth of plants can be monitored by measuring the leaf temperature. Figure 1 shows the leaf temperature is measured by IRT-P5 temperature sensor produced by apogee [6], mounted at the top of plant leaves 4 in., measuring angle is 65°, to measure the

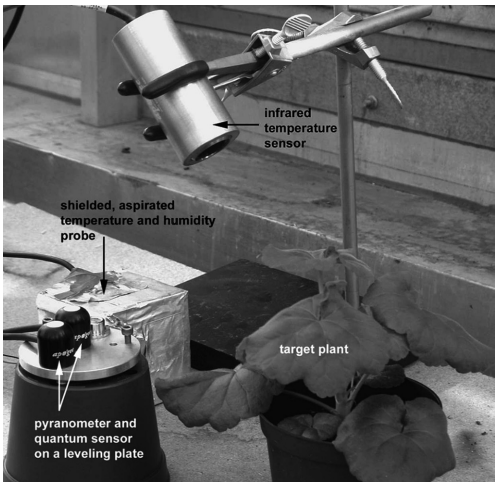

Fig. 1. Geranium plants being measured at the measurement station by Infrared radiometer

temperatures of geranium infected with the pathogen and control group. We could see that the leaf temperature of geranium infected with the pathogen was significantly higher than the temperature of control group. Then it concluded that leaf temperature could predict whether geranium Infective pathogen. In order to study the relationship between temperature and physiological index, the German TFI-50 infrared thermometer was used to measure plant leaf temperature in calm sunny weather [7]. It showed that the higher the stress was, the higher the leaf temperature became, the higher the MDA content was, the lower the content of chlorophyll became, and the physiological characters of the leaves could be judged in a certain degree. The infrared thermography was used to detect physiological parameters of plants in non-contacting and non-destructive manner [8]. Winterhalter et al. [9] used infrared thermometer (Germany, KT15D) to measure plant canopy temperature, which was used to study the high throughput detection and measurement of canopy water quality. Different temperatures were detected by infrared thermal imaging technology between infected tobacco mosaic virus TMV-U1 and uninfected leaves. The results showed that before the visual symptoms appeared the leaf temperature was 0.5–1.3 °C lower than the healthy leaf. Under controlled conditions, the difference of the leaf temperature can be used to distinguish the diseased leaves and healthy leaves. To study the changes of the biomass of three different winter rape infected with A.brassicae and A.brassicicola, the leaf temperature was measured with infrared imaging technology [10]. The results showed that the temperature of diseased leaves was 3–5 °C higher than that of the healthy leaves, in the large area, it could also find the obvious changes of lesion area temperature. Although the research process did not find that the two pathogenic bacteria had any different influence on winter rape, it was found that the thermal imaging technology had great potential in the application of the plant epidemic disease, resistance breeding and crop protection.

3.2 Application Experiment of the Leaf Temperature Sensor in the Irrigation Guidance and Drought Resistant Genotype Screening

The leaf temperature can reflect the water status of crops and guide the crop irrigation and drought resistant genotype selection. The leaf temperature was measured from the beet leaf 1 cm with the infrared thermometer (LaboratoriesC-1600 Linear) [11]. In order to promote the leaf transpiration, tried to select the new leaves when measured, and the time was in the morning 9: 00–10: 00. Study found that under drought conditions the beet leaf temperature difference is not significant between genotype and put forward that using leaf temperature difference between the condition of normal irrigation control and drought stress could better distinguish. A high resolution thermal imager was used to get maize leaves infrared image under conditions of water stress and normal irrigation and found that the leaf temperature obviously changed in two different treatments [12]. The study showed that the temperature of maize seedling could significantly reflect the drought resistance of maize under drought stress and the leaf temperature difference could be regarded as an index of drought tolerance

screening of maize at seedling stage. Figure 2 shows the thermal infrared imager of corn canopy temperature is measured and recorded to study the ability of different maize varieties to adapt to drought [13].

Fig. 2. Canopy temperature measured by infrared thermal imager

Using the portable infrared thermometer (the SK-8700) to measure corn leaf temperature [14], the visual angle is 45° and the distance from the leaf is10 cm. It studied the daily difference of corn leaf-air temperature and the relationship between the temperature and the environment factors in detail. The experiment showed that corn leaf-air temperature difference are relatively stable in full water supplied conditions, basically maintained at the range of −4.0–1.0 °C. The leaf-air temperature difference showed an increasing trend under drought stress and the difference was 5 °C between severe stress and adequate water supply. The leaf-air temperature difference can not only well reflect the moisture content of the corn plant but also be used as an important indicator of the drought state of corn (as shown in Fig. 3).

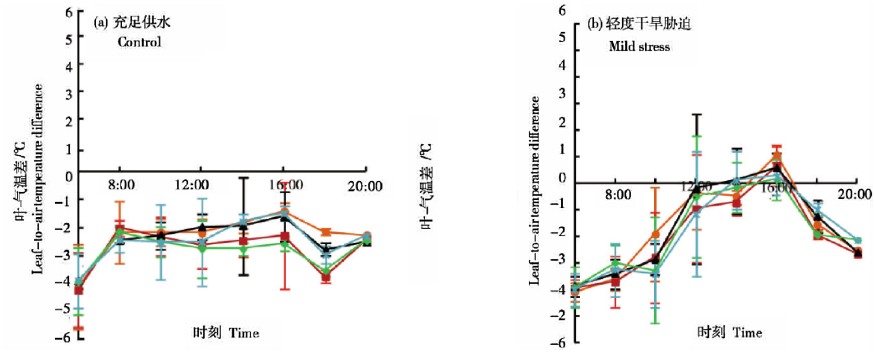

Fig. 3. Characteristic of diurnal variation of leaf-air temperature difference for maize hybrids at the stage of 13th leaf expanded under different drought stress

3.3 Application Experiment of the Leaf Temperature Sensor in Output Forecasting

The leaf temperature is also important in the output forecasting. Han et al. [15] using the BAU-I infrared thermometer to measure leaf temperature, from the side away from the rice leaf 1 cm determined, and studied the relationship between leaf temperature and water conditions at the booting stage and yield through the experiment. A hand-held infrared thermometer (domestic M312216) was used to observe leaf temperature and study the relationship between leaf temperature of early rice and late rice and production [16]. From the Table 1, the rice varieties and the cultivation measure are reasonably selected, leaf temperature of late growth period is reduced and leaf-air temperature difference are increased, rice yields will be raised. In addition, at the same growth conditions of planting density, irrigation and fertilization, genotypic differences among varieties led to the leaf-air temperature difference. Therefore, leaf-air temperature difference can be the selection index of high yield breeding for rice in different growth stages. There were many researchers who used infrared thermometer to measure crop canopy temperature, and to study the relationship between canopy temperature and canopy-air temperature difference and crop yield [17, 18].

Table 1. The correlation between leaf temperature and yield of 14:00 during rice growth period

Growth period	No-super rice		Super rice			Correlation coefficient r
	JinYou463	JinYou402	JinYou458	GanXin203	LuLiangYou996	
Leaf stage	2.2	1.8	2.1	1.7	2.3	0.5748
Differentiation	2.5	2.4	2.8	2.6	2.6	0.6734*
Heading stage	2.8	2.6	2.9	2.7	2.9	0.8329**
After heading	2.4	2.3	2.6	3.0	2.7	0.5727
Plot output/ (t/hm2)	6.71	6.22	7.45	7.12	8.11	

Note: * and ** respectively, expressed at 0.05 and 0.01 levels of significant difference.

4 The Methods of Leaf Temperature Measurement

Since modern times, scientists have studied the method of measuring plant temperatures and until now it has developed into a very mature technology. The methods include contacting measurement of temperature, non-contacting measurement of temperature and leaf temperature model. This paper mainly introduces thermal resistance temperature measurement, thermocouple temperature measurement, infrared temperature measurement, infrared thermal imaging measurement and leaf temperature model. Each method has its own characteristics, the Table 2 shows the technical parameters, advantages and disadvantages and the specific application of these methods in detail.

Table 2. Technology parameters, advantages and disadvantages of four methods of temperature measurement

Method	Product	Range	Precision	Advantage	Disadvantage
Thermal resistance	LT-1 M leaf temperature sensor	0–50 °C	0.15 °C	High precision Simple installation	resistance easily disturbed by outside environment
Thermocouple	CB-0231 thermocouple thermometer	−50–50 °C	0.05 °C	Quick reaction High precision Simple operation	Response a long time Influence leaf environment
Infrared	MI series infrared radiometer	−30–65 °C	0.3 °C	8–14 μm germanium window reduces the absorption of water vapor With the radiation shielding, minimize interference	Influenced by emissivity, distance, environment temperature and atmospheric absorption
Infrared thermal imaging	FLIR A300 infrared camera	−20–120°C	2°C	built-in analysis, alarm functionality and independent communication technology	Expensive price Poor precision

4.1 Contacting Measurement of Leaf Temperature

4.1.1 Thermal Resistance Measurement

The thermal resistance is a temperature sensor which is made of known resistance varying with temperature, such as platinum resistance temperature measurement. Thermal resistance temperature measurement often uses constant current source of three wires to drive the resistance sensor in order to obtain the voltage of thermal resistance. After voltage amplification, A/D conversion and SCM processing, the temperature of the object will be obtained. The thermal resistance is the method of contact temperature measurement, which has a lot of advantage including high accuracy, simple operation and low cost. At present, the research on using thermal resistance to measure leaf temperature is not too much. The changes of carbon dioxide concentration in winter wheat canopy were studied using TL series glass thermal resistor temperature measurement [19]. The LT-1 M leaf temperature sensor [20] (as showed in Fig. 4) has a subminiature touch probe that measures leaf temperature. The lightweight stainless steel wire clip holds high precision glass packaging thermistor, and the probe is very small and specially designed, which almost makes no effect on the natural temperature of the plant leaves. LT-1M leaf temperature sensor has high

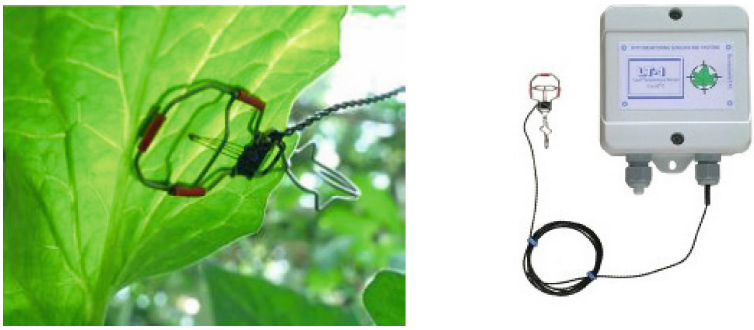

Fig. 4. The LT-1M leaf temperature sensor

measurement precision, installed simply and user can customize the length of water-proof cable, which can avoid the effect of humidity environment when measuring the leaf temperature. It can also be used in plant physiological and ecological monitoring system and photosynthesis measuring instrument.

4.1.2 Thermocouple Measurement

Thermocouple is a thermoelectric type of temperature sensor, which converts temperature signal into electric potential signal. The thermocouple temperature measurement instrument amplifies electrical signal and converts analog signal into digital signal. Then it sends data to the microprocessor, displays the results and gets the object temperature.

Thermocouple is also a method of contact temperature measurement which can be used to directly measure the crops leaf temperature. It is easily carried and operated, and its price is cheap. At present, the CB-0231 thermocouple temperature measurement instrument produced by CID eco scientific instrument co., ltd is often applied in plant leaf temperature measurement. CB-0231 [21] is a precision temperature measurement instrument which is first applied in physiological ecology and teaching in our country. According to the temperature difference and electromotive force principle, the thermocouple probe has the advantages of small volume, small heat capacity and fast response to measure the continuous trace changing temperature of the organisms. It is not only widely used in plant physiological ecology freezing injury, fruit storage and refrigeration but also used to measure the surface temperature. The CB-0231 thermocouple thermometer was used to measure the leaf temperature to study the effects of soil water stress on quercus variables leaf temperature [22].

4.2 Non-contacting Measurement of Leaf Temperature

4.2.1 Infrared Temperature Measurement

All objects above zero degree are constantly emitting infrared radiation energy to the surrounding. It is the basis of the infrared radiation temperature measurement to obtain the object surface temperature accurately by measuring its infrared energy [23]. According to the infrared radiation of the object, infrared thermometer relies on its

internal optical system to gather the infrared radiation energy on the infrared sensor and converts into electrical signal. After the amplification circuit, the compensation circuit and the linear processing, the detected object temperature is displayed in the terminal. The infrared temperature measurement system includes optical system, infrared sensor, signal amplifier and signal processing and display output. The core is the infrared sensor which converts the incident radiation into a measurable electrical signal [24].

The first infrared thermometer appeared in 1931 and its strong advantage attracted the world's attention. As early as in the 1960s he used infrared thermometer to measure the plant temperature [25]. Later researchers and ecological scholars constantly tried to measured plant leaf temperature by infrared thermometer and analyzed the physiological status of plant, and studied the growth of plant crops. Infrared temperature measurement is non-contacted and different from the traditional temperature measurement. It has advantages of quick response, high accuracy and reliability, wide range and it is not easily damaged [26]. In recent years, with the rapid and smooth development of China's infrared products market, a few foreign companies have increased the market share quickly and owned considerable advantages. The infrared temperature measurement instrument has broad market prospect and economic benefit so that its application will be more and more extensive. The MI series infrared radiometer [27] (as showed in Fig. 5) produced by the Apogee company has been widely used in plant leaf temperature measurement. Infrared radiometer receives object infrared radiant energy of probe field of view and converts it into electrical signal so that the object surface temperature will be measured of. It can quickly measure the application environment and its response time is only about 0.6 s. The recording of the germanium probe is equipped with a radiation shield, which can effectively reduce the error of the measurement data caused by abrupt changes of environment temperature. Because of high accuracy, high sensitivity and a variety of field of view, infrared radiometer is very suitable for the measurement of plant leaf temperature.

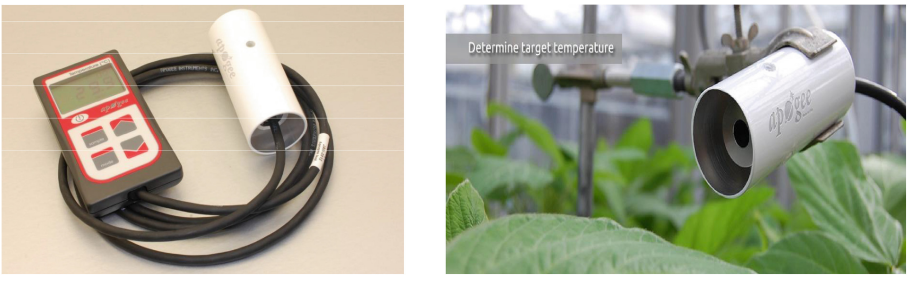

Fig. 5. Apogee MI series infrared radiometer

4.2.2 Infrared Thermal Imaging Measurement

All objects whose nature temperature is higher than the absolute zero are emitting radiated energy in the form of electromagnetic wave, including 0.7–1 μm of infrared light wave. The infrared temperature has a high temperature effect, which is the basis of

infrared thermal imaging. Infrared thermal imaging is the technology that receives infrared radiation by infrared detectors and changes to video of thermal image by signal processing system. It transforms the thermal distribution of the object into visual images and displays the gray or pseudo color on the monitor, and then gets the temperature distribution field information [28].

Since early 1980, far infrared imaging technology has firstly applied to agriculture and environmental detection. The real-time observation of plant leaves is possible with the features of multi-function, high accuracy and resolution. The application of far infrared imaging technology in plant research has caused a boom [29–31]. The results of the study were remarkable and the object of the study was also widened. The infrared thermal image (as showed in Fig. 6) is recorded with the FLIR A310 infrared camera (as showed in Fig. 7) which is produced by FLIR Systems [32], with a spectral infrared range of wavelength λ from 7.5 to 13 μm, a temperature range of −20 to +120 °C and an accuracy of ±2 %. The FLIR A300 infrared camera comes with the 18 mm standard lens providing a 25° × 19° field of view and 320 × 240 resolution. With its composite video output, the camera is a good choice for measuring leaf temperature. The FLIR A310 owns its built-in analysis, alarm functionality and independent communication technology. It has multi-camera utility software including the FLIR IP config and FLIR IR monitor.

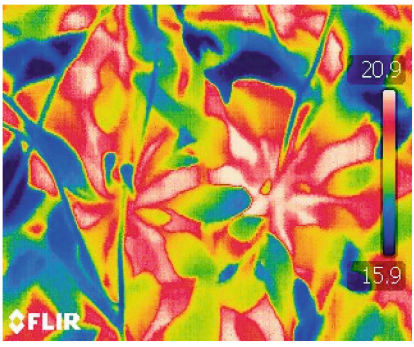

Fig. 6. The infrared thermal image of leaf

Fig. 7. FLIR A300 infrared camera

4.3 Leaf Temperature Model

The leaf temperature model is a simulation model in the greenhouse, which regards the environment conditions (air temperature, air humidity and other parameters) as the driving variable. This paper mainly introduces the model between environment temperature and leaf temperature. The model takes leaf temperature as the dependent variable and environment temperature as the independent variable, building their fitted equation. The model method has good forecast effect and can guide actual production. In foreign countries, it was feasible to control the greenhouse environment according to the leaf temperature and establish the mechanism model of the leaf temperature [33]. Yao et al. [34] established the leaf temperature simulation model based on the mechanism model of the blade energy balance.

Using the common cucumber as the experimental material in the simple sunlight greenhouse, the model of plant leaf temperature was established [35]. The study showed the change regulation of the environment temperature to leaf temperature in a day and analyzed the physiological adaptive mechanism of the leaf temperature. From the Fig. 8, the environment temperature and leaf temperature are fitted and the equation is: $y = 1.188a - 7.6662$. The 'y' was the leaf temperature and the 'a' was environment temperature, coefficient of determination was $R2 = 0.9128$. The equation was significantly associated with 0.01 levels and verified good correlation between leaf temperature and environment temperature.

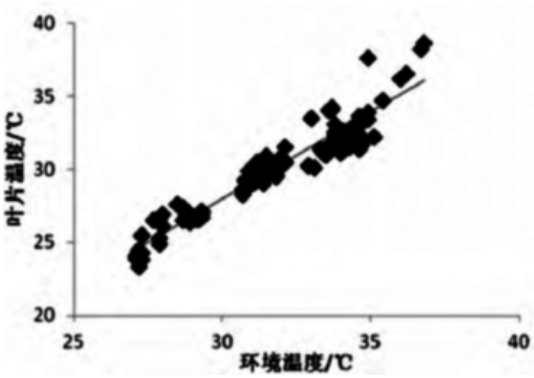

Fig. 8. The fitting of leaf temperature and environment temperature

5 Problems and Development Direction

5.1 Problems

There are many researches on the application of leaf temperature. Although the technology of leaf temperature measurement is developing and many advanced products are produced, there are some problems in the application of leaf temperature and measurement methods that are mainly reflected in the following aspects:

(1) The leading wire of thermal resistance sensor and the connecting wire of the resistance have a great influence on the measurement results. The leading wire of thermal resistance is often in the measured temperature environment which fluctuates seriously and varies with temperature. It is so difficult to estimate and correct that causes larger measurement error [36]. Because the platinum is expensive metals, it is generally used for high precision industrial measurement and rarely applied in plant temperature measurement.
(2) Because the thermocouple is belong to contacting measurement [37], it is necessary to absorb heat from the leaves and bring heat conduction, which will influence on the surface environment of leaves. Because of the disadvantages of hard workload and longtime response, the thermocouple temperature measurement is not suitable for large area measurement. In addition, contacting with the leaves easily leads to the change of the leaf environment and affects the growth of the crops and the measurement precision. Many experts and scholars measures leaf temperature by thermocouple measurements, but it is difficult for thermocouple to overcome the limitations of radiation and heat conduction. So thermocouple temperature measurement is not too widely used in plant leaf measurement.
(3) Infrared thermometer is affected by the leaf emission rate which is a very complex parameter. So it is difficult to obtain the real temperature. The result needs to be corrected for material emissivity and temperature measurement data is processed difficultly. In addition, the infrared thermometer is greatly influenced by the environment, such as dust, steam, carbon dioxide, etc. [38].
(4) There are some problems in the infrared thermal imaging technology [39]. Firstly, the infrared imaging camera depends on the temperature difference to form images, but leaf-air temperature difference is generally small, so the contrast of infrared thermal image is low and the ability of resolving details is poor. Secondly, the infrared imaging camera could not realize the target through transparent barrier, such as the window glass because it can't make the infrared imaging camera detect temperature difference. Thirdly, high cost and price is the biggest factor that limits the thermal imaging camera products widely used.

5.2 Development Direction

The research on the leaf temperature in our country started relatively late and it has not reached to the world leader level in the application and measurement of leaf temperature, so there is a lot of room for developing. Firstly, research on the application of leaf temperature is still in the primary stage and using leaf temperature to study evapotranspiration of crop, irrigation, variety breeding and yield forecast should be further improved. The application of leaf temperature should be developed toward the direction of precision agriculture. Secondly, when measuring the crop leaf temperature we should study the effects on temperature at different moments and different parts of leaves and the degree of young and old leaves may make leaf temperature different. It is the key for application of leaf temperature to measure temperature accurately. We

should pay attention to the development of leaf temperature measuring instrument and the key technology and improving the accuracy of measurement, which is the guarantee for the healthy and rapid development of our country agriculture.

6 Conclusion

Now more and more experts and scholars pay more attention to the study of crop leaf temperature, and leaf temperature has become one of the most important factors in the process of crop growth. Plant leaf temperature is one of the most important parameters of plant affecting its healthy growth. It is significant for the study on crop evapotranspiration, irrigation, variety breeding and yield forecast. In order to measure leaf temperature, thermal resistance measurement, thermocouple measurement, infrared temperature measurement, infrared thermal imaging measurement and the leaf temperature model can be used. Each method has its own characteristics in measuring the leaf temperature. Obviously, infrared temperature measurement has more advantages in leaf temperature measurement. This non-contact type of measurement has advantages of wide range and fast response and it is suitable for large area measurement. However, the factors that affect the accuracy of infrared temperature measurement, such as emissivity, distance, environment temperature and atmospheric absorption must be noticed. The accuracy of infrared sensors and the key technology must be improved. Reducing the cost of infrared instrument production and the use of infrared temperature measurement will be more common.

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