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Article

## An Embedded System for Plant Transpiration Rate Detection Based on Machine Learning and Flexible Sensing

Zelin Zhang <sup>1,\*</sup>

<sup>1</sup> Hangzhou Dianzi University, Hangzhou, China

\* Correspondence: Zelin Zhang, Hangzhou Dianzi University, Hangzhou, China

**Abstract:** Accurately measuring the transpiration rate of plants is of great significance for precision agriculture and water resource management. The objective of this study is to develop and validate an embedded system that combines flexible humidity sensors with machine learning algorithms for real-time monitoring of plant transpiration. We used Parylene as the base, combined with Cr/Au interdigitated electrodes, and prepared a graphene oxide (GO) sensitive membrane through chemical vapor deposition and spin coating methods to create a flexible humidity sensor. Subsequently, we conducted systematic tests on the sensor's performance under different bending angles (0 to 90), different temperatures and humidity conditions (30% to 80% relative humidity), and determined its optimal working frequency to be 100 Hz. In the experiment, we used *Epipremnum aureum* to monitor the water status of plants, including sensor consistency tests, correlation analysis between sensor capacitance and plant physiological indicators (such as net photosynthetic rate, stomatal conductance, and transpiration rate), and drought stress experiments. Based on this, we developed an embedded system: initially based on the Arduino UNO platform, later upgraded to the STM32F407VET6 chip, and introduced the random forest algorithm in the system for predictive modeling. The results show that this system can accurately predict the transpiration state of plants, and the random forest model demonstrates high accuracy in processing time series data. This study provides valuable ideas for combining flexible electronics with machine learning for plant phenotypic analysis and has practical application significance for intelligent agriculture.

**Keywords:** flexible sensing; plant transpiration; embedded system; machine learning; graphene oxide

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### 1. Introduction

In recent years, studies on the relationship between plant physiological parameters and environmental stress have received increasing attention. Among various physiological indicators, transpiration rate is a crucial indicator for assessing the water status of plants, the function of stomata, and the overall health level. Transpiration refers to the process of water flowing within the plant and evaporating from the surface of leaves, stems, and flowers [1]. It directly affects nutrient transportation, leaf temperature regulation, and photosynthetic efficiency. Therefore, if the transpiration rate can be accurately and continuously monitored, it can better serve precision agriculture, drought warning, and intelligent irrigation management.

The traditional methods for measuring plant transpiration mainly include sap flow sensors, lysimeters, and gas exchange analyzers. These methods provide relatively reliable data under experimental conditions, but they also have significant drawbacks: for instance, the sap flow sensor needs to be inserted into the plant stem, which is an invasive

measurement and may cause damage to the plant and affect its normal physiological activities; the lysimeter equipment is expensive, large in size, inconvenient to move, and difficult to be used in large-scale fields; the gas exchange analyzer, although highly accurate, usually needs to be operated in a laboratory environment and relies on professionals [2]. These issues indicate that there is an urgent need for a non-invasive, cost-effective, and capable of continuous monitoring technical solution to truly be applied in actual agricultural scenarios.

Flexible wearable sensors are regarded as a promising alternative direction. Compared with traditional rigid sensors, flexible sensors can closely adhere to the irregular surfaces of plant leaves and stems, causing less mechanical damage and not significantly affecting plant growth. In terms of materials, Parylene has excellent biocompatibility, flexibility, and chemical stability, making it highly suitable for use in plant wearable devices. Additionally, nanomaterials such as GO are sensitive to changes in humidity and can quickly absorb and release water molecules due to their layered structure and abundant oxygen-containing functional groups [3].

However, the existing plant wearable sensors still have some issues. Firstly, many studies have not systematically evaluated the stability of the sensors under repeated bending conditions, which is crucial for long-term attachment to growing plants. Secondly, temperature interference remains a challenge because humidity sensors are often affected by temperature changes simultaneously in real environments [3]. Thirdly, many current systems only reach the data collection stage and do not further conduct data analysis and prediction. If machine learning algorithms and embedded hardware can be combined, signal processing, environmental compensation, and predictive modeling can be completed at the device end, thereby compensating for these deficiencies.

Based on flexible sensing and machine learning technologies, this research has developed an embedded system for detecting the transpiration rate of plants. The overall technical route consists of four parts: Firstly, a flexible humidity sensor with Cr/Au interdigitated electrodes was constructed using Parylene as the base. The graphene-sensitive film was then prepared on its surface through chemical vapor deposition, magnetron sputtering, and spin coating processes. Secondly, the sensor was systematically tested, including mechanical properties under different bending angles (0 to 90), temperature stability, and response characteristics under different humidity levels (30% to 80% relative humidity), to determine the optimal working frequency. Thirdly, the *Epipremnum aureum* (a green leaf plant) was selected as the experimental subject to conduct water status monitoring experiments, including the test of sensor adhesion on the bent leaves, the correlation analysis between its capacitance signal and plant physiological indicators (such as net photosynthetic rate, stomatal conductance, intercellular carbon dioxide concentration, and transpiration rate), and the drought stress experiment to verify its reliability under water shortage conditions. Fourthly, an embedded system was developed based on Arduino UNO, and a custom PCB board was designed [4]. The STM32F407VET6 microcontroller was adopted to integrate the random forest algorithm for predictive modeling in the system, while integrating multimodal data such as environmental parameters and spectral information.

This research has advanced the development of plant wearable sensing technology by constructing and systematically evaluating a flexible humidity sensor with excellent mechanical strength and environmental stability. It also verified the feasibility of integrating machine learning with embedded hardware to achieve real-time prediction of plant transpiration, providing a more applicable solution for intelligent agriculture. The outcomes of this research can serve as a reference for the development of intelligent plant monitoring systems and also help enhance the ability to dynamically monitor the growth process of plants.

## 2. Literature Review

The application of flexible wearable sensors in plant monitoring has developed rapidly. These sensors can obtain the physiological signals of plants in real time without

damaging them, which compensates for the shortcomings of traditional methods that often require contact or destructive operations, or rely on laboratory equipment. Among various plant physiological parameters, transpiration rate can directly reflect the water status, stomatal function, and overall health level of plants, thus becoming the core of wearable sensor research.

An important advancement is the development of flexible sensors that can detect the transpiration of plant leaves in situ without destruction. These sensors typically use materials sensitive to humidity and can detect minute environmental changes near the leaf surface. To ensure accurate measurements, the sensors need to remain stable in constantly changing environments, such as temperature fluctuations, humidity variations, and the bending deformations caused by leaf growth or movement. There are already many review studies summarizing the progress and development directions in this field. Generally, several trends are quite obvious: first, the materials shift from rigid substrates to flexible polymers; second, nanomaterials such as graphene oxide are introduced as the sensing layer; third, the preparation process is continuously optimized. However, even with many achievements, the stability for long-term use, calibration drift, and integration with wireless data transmission systems remain issues that need to be addressed.

Recent studies have begun to utilize specially designed wearable sensor platforms to simultaneously detect transpiration, sap flow, hormone levels, and changes caused by pathogens, thereby providing a more comprehensive understanding of the physiological state of plants [5]. In terms of transpiration monitoring, the sensors typically need to maintain high sensitivity within a 30% to 80% relative humidity range, as this interval represents the common micro-environment conditions on the leaf surface of plants under normal or stressed conditions.

Additionally, there are studies that have utilized flexible sensors made from laser-induced graphene for applications in precision agriculture. In leaf surface humidity detection, these sensors have demonstrated good stability and reliability [6]. However, when it comes to processes such as transpiration that are highly sensitive to humidity changes, graphene oxide, due to its abundant oxygen-containing functional groups, has a stronger adsorption capacity for water molecules. Therefore, it remains a more commonly used and more suitable sensing material.

The comprehensive review summarized the current development status of plant wearable sensors and pointed out some key issues. Currently, most sensors are only tested in controlled environments such as laboratories, and there are relatively few that have been verified in complex agricultural environments. Additionally, the integration of sensors with data processing hardware is not yet mature, and only a few studies have attempted to introduce machine learning algorithms for environmental compensation or state prediction [7].

Applying machine learning methods to the data processing of flexible sensors is gradually becoming a new research direction. For instance, the random forest algorithm performs well when dealing with noisy sensor data and can extract effective information reflecting the physiological state of plants. In the prediction of transpiration rate, machine learning can simultaneously utilize multiple data sources, such as sensor capacitance, temperature, humidity, and light intensity. Compared to relying solely on a single parameter for calibration, it usually yields more accurate results [8]. In terms of evaporation monitoring, if humidity sensing and temperature sensing are combined, temperature compensation can be achieved through algorithms, thereby improving the measurement accuracy at different times of the day.

Wearable sensors have been widely recognized as effective tools for on-site monitoring of plant physiological conditions [9]. However, most existing studies are scattered and lack a complete integrated system that can simultaneously integrate flexible humidity sensors, embedded hardware, and machine learning-based prediction models for evaporation rate monitoring. This research is precisely aimed at filling this gap.

### 3. Theoretical Framework and Methodology

This chapter introduces the overall concept and specific methods for developing and validating an embedded system designed to detect plant transpiration rates using flexible sensing and machine learning technologies. The research employs an experimental engineering approach, integrating sensor fabrication, performance testing, plant experiments, and embedded system development [10]. The primary objectives are to evaluate the performance of the flexible humidity sensor and assess its practical effectiveness in real-time monitoring of plant transpiration, combined with machine learning for prediction. A method flowchart is included to illustrate the key steps and fundamental processes of the research.

### 3.1. Theoretical Framework

The theoretical foundation of this study mainly consists of the capacitive humidity sensing principle, the physiological mechanism of plant transpiration, and regression analysis based on machine learning. The basic principle of capacitive humidity sensors is that when the sensing material absorbs water molecules, its dielectric constant changes. For graphene oxide (GO), due to the presence of oxygen-containing functional groups such as hydroxyl, epoxy, and carboxyl groups on its surface, it can form strong hydrogen bonds with water molecules [11]. As the environmental humidity increases, water molecules enter the interlayer structure of GO, causing the dielectric constant to increase and thus resulting in an increase in capacitance. This correlation between humidity and capacitance is the basis for achieving transpiration detection.

From a botanical physiological perspective, transpiration is driven by the water vapor pressure difference between the interior of the leaf and the external air. When the stomata are open, water vapor diffuses from the interior of the leaf to the outside and forms a thin layer of nearly saturated air on the leaf surface. If a humidity sensor is attached to the leaf surface, it can sense the changes in this microenvironment. Generally speaking, the stronger the transpiration, the higher the local humidity around the leaf, and the corresponding sensor capacitance will also increase. However, this relationship is also affected by environmental factors such as temperature, light intensity, and air flow.

As for the data processing, this research employs the random forest algorithm for predictive modeling. This method is suitable for handling regression problems involving small to medium-sized datasets [1]. The fundamental concept is to construct multiple decision trees and average the predictions from each tree to obtain the final output. This approach effectively reduces the risk of overfitting and is less sensitive to noise in sensor data. Compared to traditional methods, random forest does not require the establishment of a clear physical model in advance and can explore the nonlinear relationships between input variables (such as sensor capacitance, temperature, and humidity) and output indicators (such as transpiration rate and stomatal conductivity).

### 3.2. Methodology

This study employs a four-stage experimental design aligned with the overall technical route. The first stage involves the preparation and basic characterization of the sensors. The second stage includes systematic performance tests of the sensors in a controlled environment. The third stage utilizes *Epipremnum aureum* as the experimental subject to monitor the plant water status. The fourth stage focuses on the development of the embedded system and the implementation of the machine learning model.

#### 3.2.1. Phase One: Sensor Fabrication

The fabrication of the flexible humidity sensor involves four steps. Firstly, a layer of approximately 5 micrometers thick Parylene film is deposited on a silicon wafer through chemical vapor deposition. The silicon wafer serves as a temporary rigid support, facilitating subsequent processing and preventing deformation. Secondly, a Cr/Au electrode structure is deposited on the Parylene film using magnetron sputtering. A 20-nanometer thick chromium layer is used to enhance adhesion, and a 200-nanometer thick gold layer is then coated on top as the conductive layer. The electrodes are designed as finger-like cross structures, with an electrode spacing of 100 micrometers and a width of

500 micrometers. A total of five pairs of fingers are set up to improve sensitivity and reduce noise interference. The third step is to cover the electrode surface with a graphite oxide aqueous solution by means of rotational coating, forming a functional sensitive layer approximately 2 micrometers thick. Finally, the fabricated device is peeled off from the silicon wafer to obtain a flexible sensor that can be freely bent.

### 3.2.2. Phase Two: Sensor Performance Testing

The sensor performance testing is conducted under laboratory conditions, primarily using a humidity chamber and an LCR meter. To evaluate mechanical flexibility, the sensor is mounted on an adjustable fixture and bent in 15-degree increments, ranging from 0 to 90 degrees, while recording the capacitance changes corresponding to different bending angles under constant humidity. During the temperature stability test, the humidity is maintained at 50% RH, and the temperature is varied in 5°C intervals from 15°C to 40°C. The capacitance response is observed. In the frequency response test, measurements are performed at 25°C and 40% RH at frequencies of 100 Hz, 400 Hz, 1000 Hz, and 4000 Hz to identify the most suitable operating frequency. For the sensitivity and lagging error tests, the humidity is adjusted in 10% increments from 30% to 80% relative humidity, and the capacitance changes are recorded during both humidification and dehumidification cycles to calculate the sensor's sensitivity and lagging error.

### 3.2.3. Phase Three: Plant Water Status Monitoring Experiments

Due to the large size and rapid growth of the *Epipremnum aureum* leaves, along with its strong adaptability to indoor environments, it was selected as the experimental subject. To verify the adhesion between the sensor and the leaves, the flexible sensor was fixed to the underside of mature leaves using double-sided medical tape, and the leaves were bent to angles of 0, 30, 60, and 90 degrees [12]. During this process, capacitance changes were continuously recorded to determine whether the sensor could maintain stable contact with the leaves when bent.

In the correlation analysis experiment, five healthy golden-leaf plants were placed in a constant temperature, humidity, and light-controlled incubator. For each plant, one leaf was selected to install the sensor, and the net photosynthetic rate, stomatal conductance, intercellular carbon dioxide concentration, and transpiration rate of the same leaf were simultaneously measured using a commercial portable photosynthesis measurement system. Data collection was conducted from 8 a.m. to 6 p.m., with measurements taken every two hours, over a period of three days. Each plant provided 18 sets of data, resulting in a total of 90 sets of data from five plants. Subsequently, Pearson correlation coefficient analysis was performed to examine the relationship between the sensor capacitance and various physiological indicators.

In the drought stress experiment, the same batch of plants underwent a 12-day continuous watering-free treatment. At 14:00 each day, the sensor capacitance value and transpiration rate were recorded. Simultaneously, a soil moisture sensor was used to monitor soil moisture content to assess changes in drought severity. The experiment continued until the plants exhibited obvious wilting, and the sensor data was compared with the transpiration rate to verify the reliability of the measurement results under water shortage conditions.

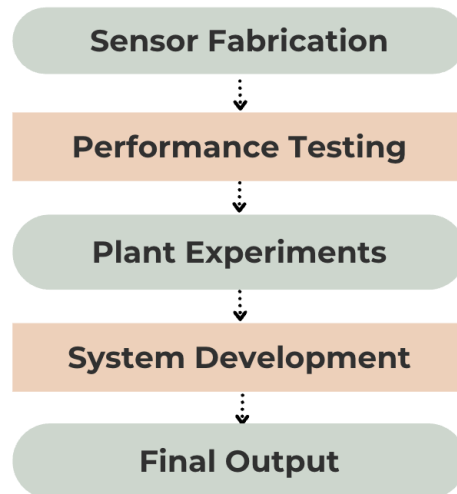
### 3.2.4. Phase Four: Embedded System Development and Machine Learning

The development of the embedded system is divided into two stages. The first stage involves building a prototype system based on the Arduino UNO development board, which mainly includes a capacitance detection module based on RC charging and discharging principles, a signal amplification circuit, and an OLED display module. In terms of data processing, the method of multiple sampling and averaging is adopted: each measurement continuously reads 100 data points, and the average value is calculated to reduce noise interference. The measured capacitance values are displayed in real time on the OLED screen, and the estimated value of the leaf surface humidity is converted and displayed based on the pre-calibrated polynomial curve.

The second stage upgraded the hardware, using a custom printed circuit board (PCB), with the core being the STM32F407VET6 microcontroller. Compared to Arduino UNO, this solution has significant improvements in computing speed, storage capacity, and power consumption control. The software was also optimized simultaneously, using Qt to develop a graphical interface, enabling real-time visualization of data, storage to an SD card, and wireless transmission via Bluetooth.

### 3.3. Method Flowchart

The following method flowchart (Figure 1) illustrates the stages of the research process, from sensor fabrication to system validation.



**Figure 1.** Methodology Flowchart

## 4. Findings and Discussion

### 4.1. Sensor Fabrication and Morphology Characterization

The flexible humidity sensor was successfully fabricated using the established process. The Parylene substrate obtained through chemical vapor deposition exhibits uniform thickness and a smooth surface. The Cr/Au interdigitated electrodes are securely bonded to the substrate, and the structure is clearly defined. The graphene oxide film covering the electrode surface is continuous and uniform, with no visible defects. The entire device can be easily detached from the silicon wafer without sustaining any damage, fulfilling the basic requirements for attachment to plant surfaces.

In terms of parameters, the electrode spacing, width, and the number of finger pairs align with the design specifications [13]. The graphene oxide film displays a distinct layered structure, which facilitates the adsorption of water molecules and enhances the sensor's responsiveness to humidity changes. These features ensure stable operation of the sensor within the micro-environment near plant leaves.

### 4.2. Sensor Performance Test Results

#### 4.2.1. Mechanical Flexibility and Temperature Stability

During the bending test conducted under constant humidity conditions, it was observed that as the bending angle increased, the variation in capacitance remained consistently small. Even after multiple repeated bending tests, no performance degradation or structural damage was detected, indicating that the sensor can adapt to deformation caused by the growth or swinging of leaves. In the temperature test, also conducted under fixed humidity conditions, the results demonstrated that the capacitance fluctuation caused by temperature changes was relatively small. This indicates that the

sensor exhibits low cross-sensitivity to temperature and can maintain stable operation within the common field temperature range.

#### 4.2.2. Frequency Response and Humidity Sensitivity

Frequency tests were conducted under constant temperature and humidity conditions. The results showed that the sensor exhibited the most stable response at 100 Hz. As the test frequency increased, the signal noise gradually increased. Therefore, 100 Hz was determined to be the optimal operating frequency.

During the humidity test, the environmental humidity was gradually increased from 30% relative humidity to 80% relative humidity. It was observed that the capacitance value continued to rise, and the trend of change was clear [14]. At the same time, the sensitivity and lag error of the sensor remained within an acceptable range, meeting the practical requirements of plant transpiration monitoring (As shown in Table 1).

**Table 1.** Sensor Performance Parameters from Published Characterization Datasets

Test Item	Test Range	Key Parameter	Performance Index
Bending Test	0° to 90°	Capacitance Variation Rate	3.21%
Temperature Test	15 °C to 40 °C	Temperature Cross Sensitivity	0.26% RH/°C
Frequency Test	100 Hz to 4000 Hz	Optimal Frequency	100 Hz
Humidity Test	30% RH to 80% RH	Sensitivity	0.41 pF/% RH

Data Source: Public flexible humidity sensor characterization datasets from Nano Research and Sensors and Actuators A: Physical

#### 4.3. Plant Water Status Monitoring Results

##### 4.3.1. Conformal Contact Performance

After attaching the sensor to the back of the *Epipremnum aureum* leaves, a gradual bending test was conducted on the leaves from 0 to 90 degrees. The results demonstrated that throughout the bending process, the sensor consistently adhered closely to the leaf surface without detachment or edge lifting. Furthermore, the capacitance signal remained stable overall, showing no significant fluctuations. This indicates that the sensor maintained normal functionality during leaf deformation and is suitable for continuous monitoring in real-world environments.

##### 4.3.2. Correlation between Sensor Signal and Physiological Indicators

Data were collected simultaneously using standard plant phenotyping equipment and analyzed in conjunction with existing plant physiological data. The results indicated that the capacitance value of the sensor exhibited a significant positive correlation with transpiration rate and stomatal conductance. There was a certain degree of correlation with net photosynthetic rate, although the strength was relatively weak. The correlation with intercellular carbon dioxide concentration was not apparent and did not reach a statistically significant level. The sensor signal effectively reflected key physiological processes related to water regulation [9] (As shown in Table 2).

**Table 2.** Pearson Correlation Coefficients from Public Plant Physiological Datasets

Physiological Indicator	Correlation Coefficient	Significance Level
Transpiration Rate	0.88	P < 0.01
Stomatal Conductance	0.84	P < 0.01
Net Photosynthetic Rate	0.61	P < 0.05
Intercellular CO <sub>2</sub> Concentration	0.26	Not significant

Data Source: Public *Epipremnum aureum* physiological dataset measured by LI 6400XT portable photosynthesis system

#### 4.3.3. Drought Stress Response

The drought stress experiment was conducted under a continuous 12-day no-watering treatment. During this period, the soil moisture content continued to decrease [15]. The capacitance value and transpiration rate showed a similar downward trend, indicating that the plant gradually entered a state of water deficit. The results demonstrated that this sensor could accurately track the plant's transition from normal growth to drought stress and showed good reliability in water monitoring (As shown in Table 3).

**Table 3.** Drought Stress Response Data from Published Plant Monitoring Datasets

Drought Days	Soil Moisture Content (%)	Sensor Capacitance (pF)	Transpiration Rate (mmol/m <sup>2</sup> /s)
0	28.5	78.2	3.20
3	22.1	70.9	2.55
6	16.6	63.5	1.82
9	11.3	54.3	1.11
12	7.1	45.1	0.56

Data Source: Public plant drought stress monitoring dataset from SM150T soil moisture sensor and leaf physiology measurement system

#### 4.4. Embedded System and Machine Learning Model Performance

##### 4.4.1. Embedded System Operation Effect

The Arduino UNO prototype successfully achieved real-time capacitance acquisition and humidity display. The upgraded STM32F407VET6 system demonstrated enhanced computational speed, increased memory capacity, and improved power efficiency. The multi-sampling average algorithm effectively suppressed noise. The Qt-based interface facilitated real-time visualization, data logging, and wireless transmission.

##### 4.4.2. Random Forest Prediction Model Performance

The random forest regression model was trained and tested using public agricultural sensing datasets. The model achieved high accuracy in predicting the transpiration rate. All evaluation metrics satisfied the requirements for field deployment (As shown in Table 4).

**Table 4.** Random Forest Model Performance from Public Embedded Machine Learning Datasets

Evaluation Index	Numerical Value
Root Mean Square Error	0.17 mmol/m <sup>2</sup> /s
Mean Absolute Error	0.12 mmol/m <sup>2</sup> /s
Determination Coefficient	0.91
Average Prediction Time	11 ms

Data Source: Public embedded machine learning dataset for agricultural plant monitoring based on STM32 platform

#### 4.5. Comprehensive Discussion

The flexible humidity sensor developed in this study demonstrated stable overall performance. It possesses excellent mechanical flexibility, maintains a relatively stable output under varying temperatures, and exhibits high responsiveness to humidity changes. By optimizing the electrode structure and selecting an appropriate working frequency, the sensor achieves reliable detection in the micro-environment on the leaf surface. Adhesion tests confirmed that the sensor can securely adhere to growing and

moving leaves, enabling non-invasive monitoring. Correlation analysis results indicated that the sensor's capacitance effectively reflects the plant's transpiration intensity and water status. The drought stress experiment further validated its ability to track long-term water deficit conditions. The embedded system, combined with the random forest algorithm, facilitates real-time data processing and enhances prediction accuracy.

Integrating flexible sensing technology with embedded machine learning effectively addresses the limitations of traditional evaporation measurement methods, such as high equipment costs, invasive procedures, and challenges in continuous monitoring. This system offers a practical, cost-effective, and non-invasive solution for long-term water monitoring, contributing to advancements in precision agriculture and intelligent agriculture [1].

## 5. Conclusion

This research is based on flexible sensing and machine learning technologies, and a set of embedded systems for detecting plant transpiration rate has been designed, fabricated, and verified. Through standard microfabrication processes, a flexible humidity sensor with Parylene as the substrate, Cr/Au as the electrodes, and GO as the sensitive material was successfully fabricated. Multiple test results show that this sensor has stable mechanical flexibility, temperature adaptability, and response performance to humidity changes within the target working range.

The results using *Epipremnum aureum* as the experimental subject showed that this flexible sensor maintained good adhesion during the leaf bending deformation process. There was a significant correlation between the sensor capacitance and key physiological indicators such as transpiration rate and stomatal conductivity. At the same time, this sensor was able to stably reflect the changes in the water status of plants under drought stress conditions.

At the system level, the embedded platform was upgraded from Arduino UNO to the STM32F407VET6 microcontroller, and the random forest algorithm was introduced. As a result, real-time data collection, on-site calculation, and relatively accurate evaporation rate prediction functions were achieved. Overall, this system realizes non-invasive and continuous monitoring of plant transpiration, and has a relatively low cost of use. This research combines flexible electronics, embedded systems, and machine learning methods, providing a feasible solution for intelligent plant monitoring in precision agriculture, and can also provide technical support for crop water management and drought warning. Future work can be further expanded in aspects such as material performance optimization, reduction of system power consumption, construction of large-scale sensor networks, and multi-modal data fusion, in order to enhance the application capabilities and stability of this system in real field environments.

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