A WIRELESS REMOTE MONITORING SENSOR FOR AGRICULTURAL ENVIRONMENT BASED ON NB-IoT
/
基于 NB-IoT 的农业环境无线远程监测传感器

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ABSTRACT

This paper describes the design and implementation of a wireless sensor based on NB-IoT (Narrow Band Internet of Things) for monitoring agricultural environmental information. The sensor is capable of real-time monitoring of four environmental parameters, including ambient temperature, relative humidity, illuminance, and CO_2 concentration. In the hardware design, sensor elements are selected based on the measurement ranges and accuracies specified in agricultural environmental monitoring industry standards. The hardware circuit is designed using the BC35-G type NB-IoT module and STM32 MCU (Microcontroller Unit). In the software design, data from the environmental parameters are collected and processed by the STM32 MCU and sent to the OneNET cloud platform through the NB-IoT module. The OneNET cloud platform enables users to view the relevant environmental data collected by the sensors using mobile phones and other mobile terminals. To test the effectiveness of the developed sensors, they were tested in a glass greenhouse at Fuyang Ziqing Agricultural Technology Co., Ltd. in Anhui Province. The results demonstrate that the sensors can accurately collect the data of relevant environmental parameters and can provide stable wireless transmission of data remotely, making them suitable for practical engineering applications. In summary, this wireless remote monitoring sensor based on NB-IoT represents a significant advancement in the field of agricultural automation. The sensor's ability to accurately monitor and wirelessly transmit data in real-time provides farmers with valuable information to optimize crop growth and maximize yields.

摘要

本文描述了一种基于窄带物联网（NB-IoT）的无线传感器的设计和实现，用于监测农业环境信息。该传感器能够实时监测四个环境参数，包括环境温度、相对湿度、照度和 CO_2 浓度。在硬件设计中，传感器元件的选择是基于农业环境监测行业标准中规定的测量范围和精度。硬件电路采用 BC35-G 型 NB-IoT 模块和 STM32 MCU 进行设计。在软件设计中，环境参数的数据由 STM32 MCU 收集和处理，并通过 NB-IoT 模块发送到 OneNET 云平台。OneNET 云平台允许用户使用手机和其他移动终端查看传感器收集的相关环境数据。为了测试所开发传感器的有效性，在阜阳紫青农业科技股份有限公司的玻璃温室中进行了测试。结果表明，该传感器能够准确地采集相关环境参数的数据，并能够提供稳定的远程无线数据传输，适用于实际工程应用。总之，这种基于 NB-IoT 的无线远程监测传感器代表了农业自动化领域的重大进步。该传感器能够准确监测并实时无线传输数据，为农民提供了有价值的信息，以优化作物生长并最大限度地提高产量。

INTRODUCTION

Real-time monitoring of agricultural environmental information provides valuable data for farmers to understand the growing environment of crops and enables precise and intelligent agriculture management. The methods used for agricultural environmental monitoring depend on the planting area and geographical location. Wired or wireless LAN technology is typically used for data transmission in facility agriculture (*Lihong et al., 2011; Feng et al., 2019*), while satellite remote sensing and other technologies are used for field agriculture due to the vast area (*Sishodia et al., 2020*). Some researchers have explored the use of UAV remote sensing technology in field agricultural environment monitoring (*Radoglou-Grammatikis et al., 2020*).

In recent years, short-range wireless communication technology has been applied to the field of agricultural environmental monitoring.

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For instance, Du et al. proposed a low-power Bluetooth gateway system to monitor breeding environments in a large pig farm equipped with LAN *(Du et al., 2021*). Wang et al. developed a monitoring system for agricultural greenhouses based on ZigBee technology and particle filter optimization to reduce measurement errors (*Wang et al., 2021*). Liang et al. proposed a dynamic monitoring method for greenhouse environments using WiFi to remotely monitor parameters such as temperature, relative humidity, and illumination (*Liang et al., 2018*). To meet the needs of agricultural production, Wang et al. designed a wireless sensor network system for meteorological monitoring using LoRa communication technology (*Wang et al., 2020*). Yang et al. designed a greenhouse remote monitoring system based on NB-IoT and uploaded data to the cloud platform, facilitating the viewing of environmental monitoring data on mobile terminals (*Yang et al., 2021*). Some researchers summarized the characteristics of these short range wireless communication technologies, including Bluetooth, ZigBee, WiFi, LoRa, and NB-IoT (*Farooq et al., 2019; Mekki et al., 2019; Tang et al., 2021; Elijah et al., 2018*). Here, the characteristics of these wireless communication technologies were also summarized, focusing on their application in agricultural environmental monitoring, as shown in Table 1.

Table 1

The characteristics of existing wireless communication technologies

Type	Transmission range	Maximum data rate	Communication quality
Bluetooth	<100m	3Mbps	High
ZigBee	<1km	250kbps	Low
WiFi	100m	10Mbps	High
LoRa	5km	50kbps	Low
NB-IoT	15km	200kbps	High

Both Bluetooth and WiFi have high communication rates, so they are very suitable for transmitting information such as agricultural images. However, their transmission ranges are very short, which severely limits their application in the field of agricultural environmental monitoring. In contrast, ZigBee wireless communication technology has a longer transmission range, making it suitable for small-scale facility agriculture. However, ZigBee is a low-rate wireless communication technology that is not suitable for transmitting image information, but can meet the wireless transmission of agricultural environmental parameter monitoring data. LoRa has a longer communication distance, but its data transmission speed is also lower. NB-IoT has the longest communication distance, and its data transmission rate is similar to ZigBee, and significantly superior to LoRa. Currently, both LoRa and NB-IoT are low-power WAN communication technologies with broad development prospects (*Sinha et al., 2017; Popli et al., 2018*).

Compared to LoRa, NB-IoT has the advantages of high communication quality and long communication distance. The sufficiently long communication distance not only makes NB-IoT suitable for facility agriculture, but also for field agriculture. Excellent wireless communication quality is desired in the field of agricultural environmental monitoring and control. Compared to the transmission of environmental monitoring data, the transmission of control command information has high requirements for the quality of wireless communication to ensure reliable control of environmental control devices, and NB-IoT can well meet this requirement. The disadvantage of NB-IoT is that it requires a small amount of annual fees to be paid annually, but generally no more than EUR 2, which many businesses and individuals can fully afford.

In this paper, the focus was on the design and implementation of a wireless sensor system for monitoring agricultural environmental parameters using NB-IoT technology. The novelty of our research lies in the integration of four environmental parameters, namely air temperature, relative humidity, CO_2 concentration, and illuminance, into one compact and easy-to-use system. Additionally, our system features excellent wireless communication quality, making it well-suited for use in both facility and field agriculture. Compared to existing research on IoT-based environmental monitoring systems, our system offers a unique combination of features and performance, providing accurate and real-time data for environmental control and decision-making in agriculture.

MATERIALS AND METHODS

Architecture of remote monitoring system based on NB-IoT

The Internet of Things (IoT) has been widely utilized in various fields, but there is still no unified standard architecture. Different IoT system architectures exist in different application fields (*Burhan et al., 2018; Raj et al., 2021; Silva et al., 2018*).

Even for the same engineering problem, the architecture of IoT systems can still differ from different perspectives. Various IoT architectures have been proposed so far (*Samizadeh Nikoui et al., 2021*). In the field of agricultural environmental monitoring, the architecture of IoT systems can be divided into five layers, as illustrated in Figure 1. The perception layer is located at the bottom, where various sensors detect real-time environmental information, such as temperature, humidity, illuminance, CO_2 concentration, etc. The edge computing layer is composed of microcontrollers or microprocessors in various sensor nodes. In the edge computing layer, the microcontroller obtains environmental information from the various sensor nodes in the perception layer. Data compression is one of the main tasks of the edge computing layer. Data compression can reduce both the wireless transmission of useless data and the communication energy consumption, thus avoiding bandwidth congestion and reducing the amount of data involved in cloud computing.

The transport layer is primarily composed of 4G/5G base stations and the internet, and its function is to receive the data sent by the edge computing layer and reliably transmit them to the cloud server. In the cloud computing layer, in addition to the functions of storing massive agricultural environmental information data, complex tasks such as crop yield prediction, disease and pest prediction can also be accomplished by deep learning and other methods. The top layer is the application layer. Users can access the cloud through mobile phones, iPads, computers, and other terminals to view relevant environmental information remotely.

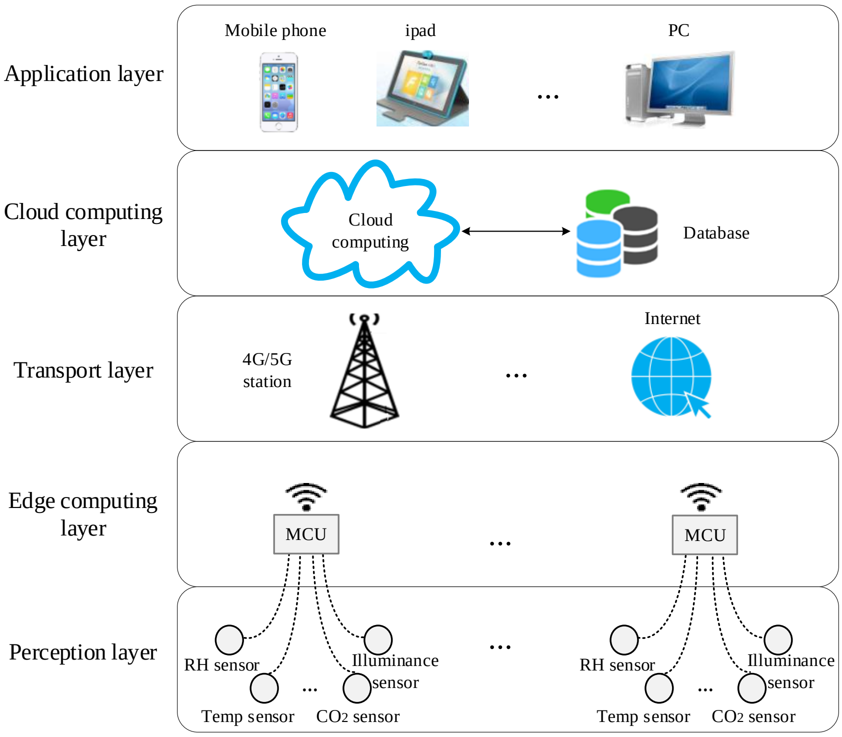


Fig. 1 - The monitoring system architecture of agricultural environment based on NB-IoT

Hardware design of wireless sensor

Environmental parameters vary in different agricultural fields, and growers' concerns depend on the type of crops or livestock. In crop farming, environmental parameters of interest include air temperature, relative humidity, illuminance, CO_2 concentration, and soil moisture. In livestock breeding, farmers may be more interested in parameters such as ammonia and hydrogen sulfide concentration, in addition to air temperature, humidity, illumination, and CO_2 concentration. For our design, the focus was on the four common parameters of air temperature, relative humidity, illuminance, and CO_2 concentration, while also reserving communication interfaces for other environmental sensors on the hardware circuit.

When selecting sensors for specific environmental parameters, various types of sensors are available, and the choice should depend on the specific application's environmental characteristics and technical specifications in relevant national, industry, and local standards. For example, Taizhou City's latest local standard, DB3212T 2024-2021 Technical Specifications for the Construction of Facility Plants Networking (*Taizhou Local Standards, 2021*), provides measurement requirements for environmental parameters such as air temperature, relative humidity, illuminance, and CO_2 concentration in the agricultural IoT monitoring field.

Table 2 shows the main measurement requirements, including the measurement ranges, accuracies, working temperature and humidity ranges, and other relevant factors.

Table 2

The main measurement requirements of agricultural environmental parameters

Environmental parameters	Measurement range	Measurement accuracy	Working temperature range	Working relative humidity range
Temperature	-10°C~65°C	±0.4°C	----	----
Relative humidity	0%~100%	±3%	----	----
Illuminance	0~200000 lux	±7%lux	-10~50°C	0~95%
CO_2 concentration	0~5000 ppm	±2% (20ppm reading)	-10~50°C	0~95%

The measurement requirements outlined in Table 2 serve as an important basis for selecting appropriate sensing devices. However, there are other factors that should also be considered when selecting the appropriate sensor devices, such as price and ease of use.

After comparing several typical sensor devices, the SHT30 digital sensor module was selected for temperature and humidity measurement. The temperature and humidity measurement ranges of the SHT30 sensor device are -40~125℃ and 0~100%, respectively, with measurement accuracies of ±0.3℃ and ±2.0%, respectively (Datasheet of SHT3x sensor, 2016), which meet the measurement requirements specified in Table 1. The physical photo of the SHT30 sensor module is shown in Fig.2. The sensor module is connected to the STM32 MCU through an I^2C interface, and the specific interface circuit is shown in Fig.3. The SCL pin serves as the serial clock signal input terminal, while the SDA is the serial data transmission pin.

Fig. 2 - The SHT30 sensor module

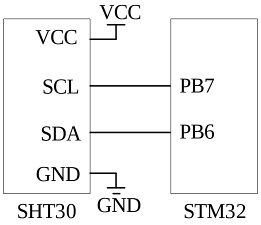


Fig. 3 - The interface circuit between SHT30 sensor and STM32 MCU

There are various types of illuminance sensors available on the market, including TSL2561 and BH1750, which have been used in previous research designs (*Bachuwar et al., 2018; Arvind et al., 2020*). However, the measurement ranges of these sensors, which are all 0-66535lx, do not meet the requirements outlined in Table 1, as the illuminance at noon on sunny days in most regions of China exceeds 10000lx in summer. Therefore, the B-LUX-V30B illuminance sensor module was chosen, having a measurement range of 0-200000 lx, a measurement accuracy of 4%, and a working temperature range of -40~85℃, with no specific requirements for humidity environment (Instructions of the B-LUX-V30B illuminance sensor). This sensor module meets the measurement requirements given in Table 1.

The physical photo of the B-LUX-V30B sensor module is shown in Fig.4, and it also uses the I^2C communication interface.

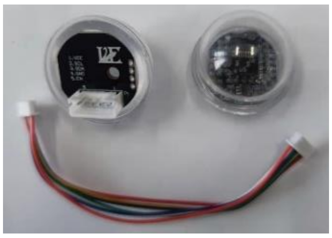


Fig. 4 - The B-LUX-V30B sensor module

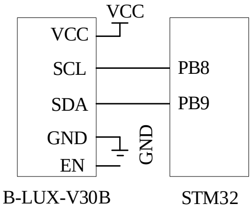


Fig. 5 - The interface circuit between B-LUX-V30B sensor and STM32 MCU

Although the STM32 MCU has two I2C interfaces, the common GPIO (General-purpose input/output) pins of the STM32 MCU were used to connect with the illuminance sensor module to make it easier to add other sensor devices in the future, such as soil sensors, etc. The sensor data acquisition can be simulated in software by implementing the I2C communication timing. The interface circuit between the B-LUX-V30B sensor module and the STM32 MCU is shown in Fig.5, and the sensor module has an enable pin (EN) that is valid for high level and can be connected to high level or suspended.

For the CO_2 concentration measurement, the JX_CO2_102 sensor module was selected after comparing various types of sensors. The measurement range is 0~5000 ppm, and the measurement accuracy is 2% of the measurement range. The working temperature range is -1060℃, and the working humidity range is 0~95% (Instructions of the JX_CO2_102 CO_2 concentration sensor). It meets the measurement requirements given in Table 1. The physical photo of the JX_CO2_102 type sensor module is shown in Fig.6. The sensor has the function of automatic zero calibration, which is convenient to use. The sensor module has three output signal modes, namely, analogue voltage signal, UART (Universal Asynchronous Receiver/Transmitter) signal, and PWM (Pulse Width Modulation) signal, and the UART mode is selected for our design. The interface circuit between the sensor module and the STM32 MCU is shown in Fig.7. The PA2 and PA3 pins are the TX pin and RX pin of the UART interface of the STM32 MCU, respectively.

As for the narrowband IoT module, the BC35-G NB-IoT module was selected, which is a multi-band wireless communication module with high performance and low power consumption. The NB-IoT module supports B1/B3/B8/B5/B20/B28 bands, and the size is only 23.6mm×19.9mm×2.2mm. To simplify the hardware circuit design, a development board with this model of NB-IoT module as the core board was selected, which is equipped with the STM32F103 single-chip microcomputer. In addition to the NB (Narrow Band) module and the STM32 MCU, there are some other interface circuits and GPIO pins led out on the development board, which is convenient for future functional enrichment.

Fig. 6 - The JX_CO2_102 sensor module

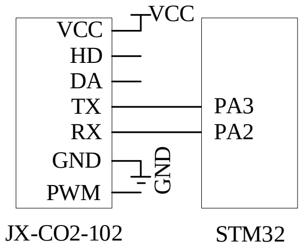


Fig. 7 - The interface circuit between JX_CO2_102 sensor and STM32 MCU

The hardware circuit of the sensor node has been designed based on the information provided above. To ensure practical application, the circuit system has been enclosed in a waterproof junction box with a round hole at the top centre, suitable for the diameter of the illumination sensor. Both the SHT30 type sensor module and the JX_CO2_102 sensor module have been positioned outside the box to enable real-time monitoring of temperature, humidity, and CO_2 concentration. Two holes have been made in the bottom centre of the box to allow the two sensor modules to extend out of the box, and PG series waterproof connectors have been used to secure the modules. To eliminate the impact of solar radiation on the measurement accuracy of temperature and humidity, a multi-layer radiation shield has been fixed at the bottom of the box, with the two sensors placed in the middle of the radiation shield.

Software design of wireless sensor for agricultural environment

The program for the node circuit was developed using Keil professional software. The primary function of the sensor node is to periodically collect information on four environmental parameters, process the data using the STM32 MCU, and wirelessly transmit the processed data to the cloud through the NB module.

The main program completed by the STM32 MCU includes system initialization, timer settings, and other related tasks. System initialization includes initializing the GPIOs connected to each sensor module, initializing the timers, initializing each sensor module, and initializing the NB module. In the timing interrupt subprogram, environmental data acquisition and wireless transmission are completed. The flow of the timing interrupt program is illustrated in Fig.8.

After collecting data from the three sensors, the STM32 MCU processes the data and combines them into a data packet, then attempts to connect to the cloud server. If a connection fails, the MCU re-establishes the connection until it succeeds, and then sends the data packet to the cloud.

The process of collecting temperature and humidity data is described as follows. The SHT30 sensor has two measurement modes: single shot mode and periodic data acquisition mode. In order to reduce the energy consumption of the sensor module, the single shot mode was adopted. Firstly, the STM32 MCU sends a data acquisition command to the SHT30 sensor. After the measurement is completed, the MCU obtains a sampling value through the read command. Then, the SHT30 sensor enters the idle state. To ensure high detection accuracy, the command 0x2C06 was used, which has the highest reproducibility and a relatively long delay time of about 20 ms. For more detailed data reading flow, please refer to SHT30 work sequence flow (Datasheet of SHT3x sensor, 2016). The temperature value and humidity value obtained are both two bytes. The temperature value is denoted as temp, and the relative humidity value is denoted as hum.

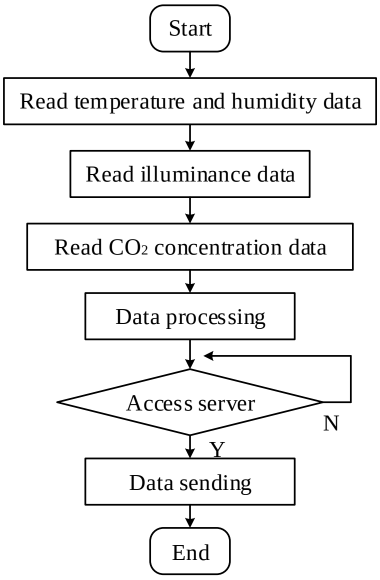


Fig. 8 - The main program flow completed by the STM32 MCU

The calculation formulas for converting the temperature value T[°C] and relative humidity RH[%] are shown in Equation (1) and Equation (2), respectively.

$$T[°C] = -45 + 175 \times temp/(2\text{^}16 - 1) \tag{1}$$

$$RH[\%] = 100 \times hum/(2\text{^}16 - 1) \tag{2}$$

The collecting process of illuminance data is described as follows. When data acquisition is not being performed, both SDA and SCL are high. When data acquisition starts, the STM32 MCU sends a start signal to the B-LUX-V30B illuminance sensor. Specifically, when SCL is at a high level, SDA changes from a high level to a low level. Then, the MCU sends the device address signal and data reading command to the illuminance sensor successively and obtains 6 bytes of data from it. Since the data directly obtained from the sensor contains 3 decimal places, the measured value needs to be divided by 1000 to obtain the correct illumination value. In the actual design, the illumination sensor module is sealed in a transparent housing to protect it. Since the enclosure attenuates the illumination to a certain extent, it is necessary to correct the measured data. The manufacturer has provided a correction factor of 1.4.

The measured value of illuminance is denoted as "light," and the calculation formula for obtaining the actual value L[lux] is shown in equation (3).

$$L[lux] = light/1000 \times 1.4 \tag{3}$$

The collection process for CO_2 concentration data is as follows: the JX_CO2_102 sensor has two operating modes - active reporting mode and passive response mode. In the active reporting mode, the sensor sends the current concentration value once every second. In contrast, in the passive response mode, the sensor measures the current CO_2 concentration only when the MCU sends the data measurement command to the sensor. To reduce energy consumption, the sensor is set to work in the passive response mode. The sensor returns the CO_2 concentration value in parts per million (ppm), with numbers in different counting units presented in ASCII code. The concentration value of CO_2 can be obtained after simple conversion.

Experimental setup

The designed system was completed with the support of the Agricultural Science and Technology Innovation Project of Anhui Province and other projects. The system was installed in a large glass greenhouse at Fuyang Ziqing Agricultural Technology Co., Ltd. The greenhouse measures approximately 130 m in length and 50 m in width, and the plants being cultivated are longevity flowers.

The sensor nodes are powered by an AC 220V to DC 5V power circuit, which is easily accessible in the greenhouse. This ensures stable sensor operation and reduces the impact of factors such as power instability. Eight sensor nodes were developed, which are uniformly deployed in the 130 m x 50 m glass greenhouse of Fuyang Ziqing Agricultural Technology Co., Ltd. The greenhouse is used for cultivating longevity flowers. The sampling period is 5 minutes, and after the successful system debugging, an actual test experiment is conducted. The monitoring period is from 0:00 on April 23, 2022, to 0:00 on April 28, 2022, for a total of five days. Some field photos of the sensor nodes are shown in Fig.9.

Fig. 9 - Some wireless sensor nodes in the field experiment

The eight sensor nodes are registered on the open cloud platform OneNET, and the detected data of environmental parameters can be displayed in various forms such as instrument panel, table, etc. An example of data display is shown in Fig.10, taken from a screenshot of a mobile phone.

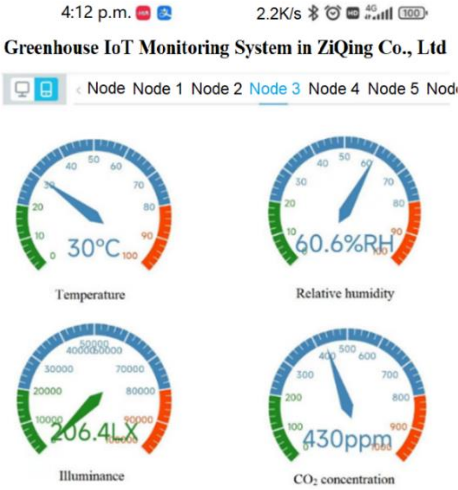


Fig. 10 - The real time environmental data displayed in the form of instrument panel

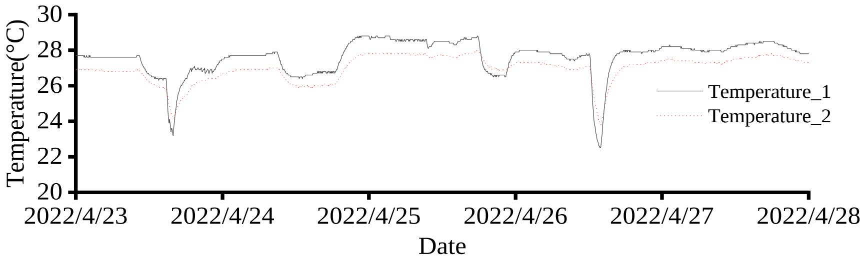
An automatic temperature and humidity recorder of type RC-4HA was used and placed alongside the 8 sensor nodes in the same greenhouse for simultaneous measurement. The purpose was to compare the temperature and humidity data measured by the designed sensor nodes with that of the recorder, which would help verify the accuracy of the sensor nodes' measurements to some extent.

RESULTS

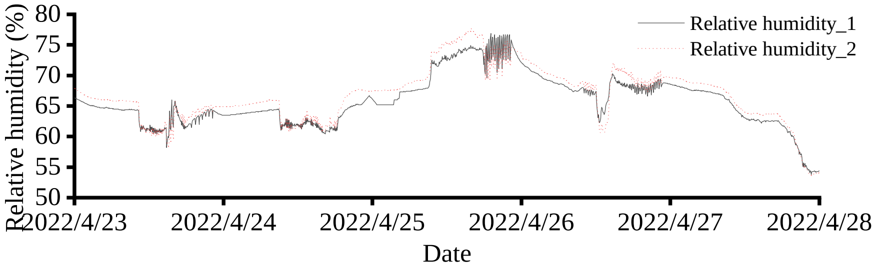
The measured data collected over the five-day monitoring period was exported from the OneNET cloud platform. With a sampling period of 5 minutes, there were 1441 sets of data. The curve displays of the four environmental parameters after mean filtering are shown in Fig.11, which includes the measured data of the RC-4HA type recorder. The black solid lines "temperature_1" and "relative Humidity_1" represent the data detected by the SHT30 type sensors, while the red dotted lines "temperature_2" and "relative humidity_2" represent the data detected by the RC-4HA recorder. The RC-4HA automatic recorder uses a temperature and humidity sensor of SHT11 type, with a temperature measurement accuracy of ±0.4°C and a relative humidity measurement accuracy of ±3.0%.

During the five-day monitoring period, each sensor node successfully uploaded 1441 sets of measured data without any loss of data packets. This shows that the designed sensor nodes can achieve real-time monitoring and reliable transmission of environmental parameters and demonstrates the high wireless communication quality of NB-IoT technology. Compared with other low-rate wireless local area communication technologies, NB-IoT technology has a significant advantage in wireless communication quality. This advantage is not only important for environmental monitoring but also for the regulation of environmental parameters in the future.

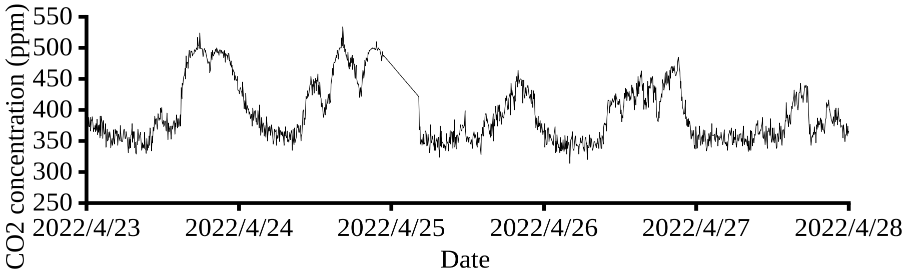
The deviation of the data average value collected by the designed sensor nodes compared to the measured data of the RC-4HA automatic temperature and humidity recorder can be calculated. The mean square error (MSE) and maximum absolute error (MAE) are shown in Table 3. The MSE and MAE of temperature measurement deviation were 0.55°C and 0.71°C, respectively, while the MSE and MAE of relative humidity were 2.01% and 1.25%, respectively. These measured deviations are normal when considering the measurement accuracy of the RC-4HA automatic recorder and the SHT30 type sensor used in the designed sensor nodes. Furthermore, all three sensor modules used in the sensor nodes have calibration functions internally, and their outputs are digital signals. Therefore, accurate measurement results can be obtained by using the calculation formula given in their instructions. The experimental results show that the designed sensor nodes can be used for real-time monitoring of agricultural environmental parameters.



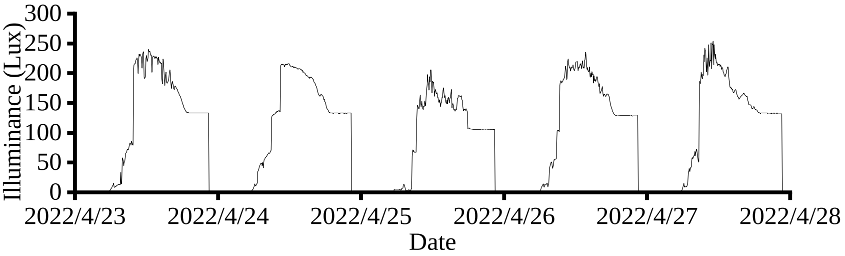
(a) The measured data of temperature



(b) The measured data of relative humidity



(c) The measured data of CO_2 concentration



(d) The measured data of illuminance

Fig.11 - The measured data of environmental parameters

Table 3

Measurement deviation of temperature and humidity

Environmental parameters	MSE	MAE
Temperature	0.55°C	0.71°C
Relative humidity	2.01%	1.25%

The AC 220V to DC 5V power supply was chosen in the experiment to prevent monitoring results from being affected by unstable power supply. In future practical applications, wired power supply can still be used, especially in facility agriculture where 220V AC power is commonly available. However, for field agriculture, a solar power supply circuit would be necessary. This can be easily achieved in practice.

CONCLUSIONS

The wireless sensor nodes designed in this study utilize NB-IoT technology to monitor and transmit real-time and accurate data on air temperature, relative humidity, CO_2 concentration, and illuminance. The system demonstrated excellent wireless communication quality, indicating the potential for widespread use in wireless remote monitoring of agricultural environments. Users can easily access the data through cloud platforms and other Internet-connected devices. The system's existing hardware provides a foundation for future data analysis and acquisition, with reserved GPIO pins available for the addition of soil sensors and control equipment. Future developments will include the design of a solar power supply circuit to expand the system's applicability beyond facility agriculture to field agriculture, providing valuable environmental data for agricultural decision-making.

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