Leveraging AIoT Visual Analytics for Optimizing Agricultural Sustainability and Efficiency

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Abstract

Bemisia tabaci is an essential pest in global agriculture, and its reproduction and distribution are affected by meteorological conditions, causing severe damage to economic crops. This study constructed a micro-meteorological station and a visualized weather alert system combining narrow-band Internet of Things (NB-IoT) and message queuing telemetry transmission (MQTT) technologies in an orchard to achieve precise pest monitoring and early warning. The micro-weather station can record high-resolution meteorological data (e.g., temperature, humidity, soil moisture, sunlight intensity, etc.) and transmit them stably and efficiently via NB-IoT and MQTT technologies to ensure real-time data updates over long distances. The early warning system combines artificial intelligence (AI) and geographic information system (GIS) to analyze the impact of meteorological conditions on *Bemisia tabaci*, make risk predictions, and provide prevention and control recommendations, such as adjusting pesticide application strategies to reduce losses and pollution. This study demonstrates an innovative agriculture solution based on NB-IoT and MQTT, which realizes data-driven and intelligent pest management in orchards, improves monitoring accuracy and control efficiency, and is not only applicable to whitefly control but can also be extended to other pests and diseases, providing an efficient and sustainable technology example for agricultural pest management.

Keywords: Bemisia tabaci formosana, Micro Weather Stations, Narrowband Internet of Things (NBIoT), Ecological Protection, Internet of Things (IoT)

1. Introduction

Bemisia tabaci (*B. tabaci*) secretes honeydew that coats the surface of the crop, providing a substrate for the growth of *B. tabaci*. This results in a black mold covering the surface of the crop, which affects photosynthesis and reduces the value of the commodity. *B. tabaci* is incredibly reproducible, forming large populations quickly under favorable conditions, and is resistant to various chemical pesticides, making prevention and control more difficult, increasing the use of pesticides and further aggravating the burden on the environment and agroecosystems. Global climate change, the increase in greenhouse environments, and the intensification of farming have all contributed to the reproduction and spread of *B. tabaci*, exacerbating the threat it poses to crops.

B. tabaci infestations devastate the yield and quality of economic crops, resulting in reduced incomes for farmers, lower market value of crops, and destabilization of agricultural ecosystems. Therefore, prevention of *B. tabaci* has become a substantial focus of agricultural research, including biological control (e.g., the use of natural enemies), improvement of agro-ecological environments, optimization of crop structures, and the development of *B. tabaci*-resistant varieties to minimize the damage caused by *B. tabaci* to crops, to safeguard food security, and to promote the sustainable development of the agricultural industry.

The reproduction and distribution of *B. tabaci* are influenced by meteorological factors such as temperature, humidity, soil moisture, and sunlight, which are crucial in regulating its population dynamics and impact. A micro-meteorological station was established in an orchard to collect high-resolution data on temperature, humidity, soil moisture, and sunlight to monitor these factors. This allows for modeling the relationship between *B. tabaci* populations and weather conditions and understanding how climate change affects population fluctuations.

The Visual Weather Alert website utilizes this data for real-time analysis and risk prediction, providing orchard managers with early warnings and recommendations. These include optimizing pesticide application timing, enhancing pest prevention measures, and improving crop management strategies to minimize damage caused by *B. tabaci*. The system integrates historical data and current meteorological conditions to offer targeted and actionable insights.

By combining precise meteorological data with ecological models, this approach fills gaps in traditional pest control strategies, quantifying the impact of climate conditions on *B. tabaci*. The system also supports smart agriculture by improving management efficiency, reducing pesticide use, and promoting sustainable agricultural practices. Beyond managing *B. tabaci*, this study serves as a model for digital and intelligent pest control applicable to other pests and diseases.

2. Research Methods

The system adopts solar power technology to realize a self-sufficient power supply and reduce the dependence on electricity for outdoor work. In addition, to effectively collect and transmit data, we compared the advantages and disadvantages of two transmission modes, the LoRa communication module and NB-IoT (Narrow Band Internet of Things), to ensure data transmission's stability and low power consumption. The advantage of this method is that it cannot only collect environmental data on *B. tabaci* growing environment stably for an extended period but also minimize the disturbance to the environment caused by manual observation.

2.1 Hardware Architecture Design

In the early stage of the study, we designed the first version of the device for environmental monitoring (shown in Fig. 1), which uses a LoRa communication module to transmit the monitoring data to the server. Due to the lack of stable network connection and power support in some monitoring sites, the operation of the first version of the device was limited by the network and power supply, which could not satisfy the long-term monitoring needs. To solve this problem, we further optimized and developed the second version of the device (shown in Fig. 2). This version introduces NB-IoT (Narrow-Band Internet of Things) technology, enabling the device to operate independently on a low-power cellular network without relying on external infrastructure. The device is also equipped with a solar power module to realize a self-sufficient power supply, which prolongs the device's operating life and reduces manual maintenance. We have upgraded the environmental sensors to improve the equipment's environmental adaptability and durability. The original light and temperature/humidity sensors have been replaced with a waterproof design to ensure stable operation in harsh environments such as high humidity and rain. This improvement improves the device's reliability and expands its range of applications, providing higher-quality monitoring data for subsequent data analysis.

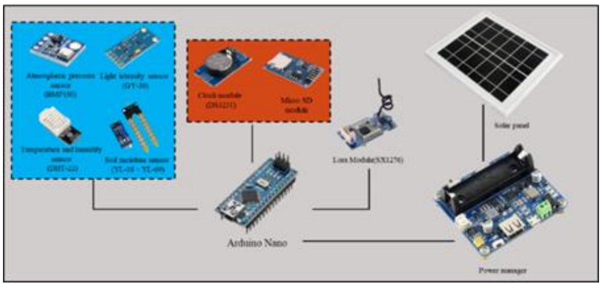


Fig. 1 First version of the device(LORA)

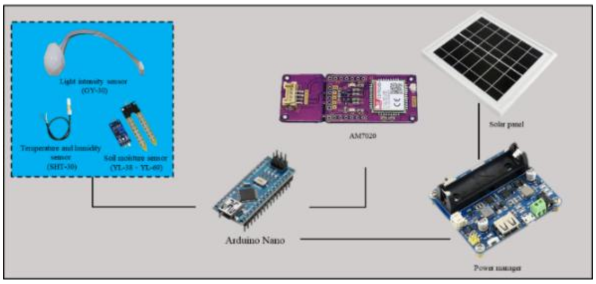


Fig. 2 The second version of the device (NB-IOT)

2.2 NB-IOT

Narrowband Internet of Things (NB-IoT) is a low-power wide-area (LPWA) technology designed for large-scale IoT deployments, offering efficient and environmentally friendly connectivity. As part of the LTE network [1], NB-IoT is a leading solution for machine-to-machine (M2M) communication due to its low power consumption, wide coverage, and cost-effectiveness, making it ideal for IoT applications.

NB-IoT's low energy consumption also makes it an environmentally friendly choice for IoT, contributing to innovative city development. It enables efficient device connectivity for energy management, environmental monitoring, and intelligent transportation, supporting the ITU-T's vision of sustainable smart cities [2]. These cities leverage ICT and innovation to improve quality of life, urban efficiency, and competitiveness while addressing current and future generations' economic, social, environmental, and cultural needs. NB-IoT serves as a vital foundation for achieving these goals.

2.3Communication Protocol

MQTT is a lightweight publish/subscribe communication protocol widely used in IoT and messaging applications, with implementations like Mosquitto (lightweight open-source broker), Hive-MQ (enterprise-grade broker), and Paho MQTT (open-source client library) [3]. Its core feature is the MQTT agent, which manages client communication and distributes messages based on subscribed topics, enhancing data transmission efficiency and reliability [4].

Experimental results (Table 1) show that MQTT significantly reduces power consumption and bandwidth requirements compared to HTTP and HTTPS while ensuring stable and efficient data transmission. This makes it ideal for large-scale IoT applications, especially in resource-constrained environments like cellular networks.

Table 1. Communication Costs.

	MQTT	HTTP GET	HTTP POST
data traffic	0.244K	1.12k	1.337K
30MB transmissions	125,523 times	27,422 times	22,971 times
Transmitted every minute	Can use 87 days	Can use 19 days	Can use 16 days
Transmitted every five minutes	Can use 435 days	Can use 95 days	Can use 80 days
Cost per 100 times	0.079 NT	0.364 NT	0.435 NT

2.4Automation Tools

Node-RED is an open-source Internet of Things (IoT) development tool based on Node.js, which is widely used for real-time processing and automated sensor data management [5]. With its flow-based programming visualization interface Fig. 3), developers can quickly build data collection, processing, and transfer applications without writing large amounts of code.

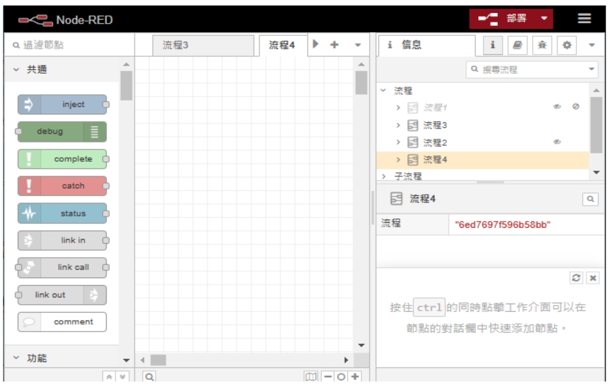


Fig. 3. Programming Visualization Interface

In this study, an automated data processing system is integrated using Node-RED (Fig. 4), which subscribes to the sensor data via the MQTT protocol and forwards the processed information to an SQL database for storage via HTTP. The system integrates LINE communication to push critical alert messages to users in real-time, realizing fully automated data management and notification [6], which enables users to track farm conditions in real-time from any location, improving management efficiency and decision-making accuracy [7].

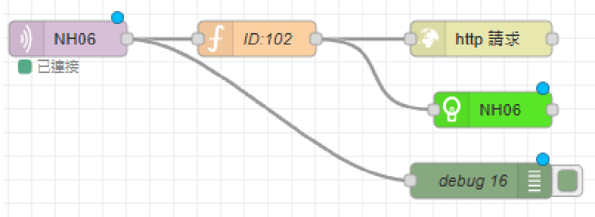
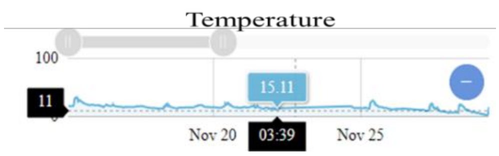
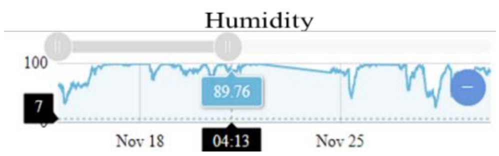


Fig. 4. Automated Data Processing System

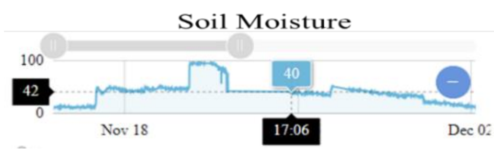
This study adopts HTML5 as the primary development framework, combining CSS and jQuery technologies to realize visual design and animation effects. CSS is used for page beautification to ensure a flexible and attractive interface, while jQuery handles dynamic effects and interactive functions to enhance user experience. The collected data is processed by a visualization tool and presented in graphs and charts, including temperature, humidity, soil moisture, and light intensity (Fig. 5). In addition, the system supports users to adjust the viewing time and select specific data points to facilitate flexible viewing of historical data and detailed analysis.



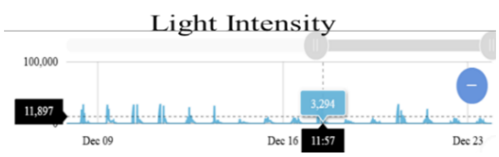
a. Temperature data curve



b. Humidity data curve



c. Soil moisture data curve



d. Light Intensity data curve

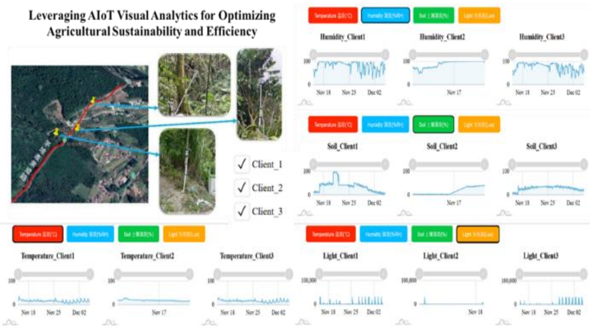


Fig. 5. Web Visualization Interface

3. Conclusions

This study successfully implemented a micrometeorological station and a visual weather alert system integrating NB-IoT and MQTT technologies to monitor whitefly infestations in orchards with high accuracy and risk prediction. The micrometeorological station captures precise weather changes, while NB-IoT ensures stable long-distance data transmission even in areas with limited infrastructure. MQTT enhances data transmission efficiency and supports simultaneous multi-device operations, enabling large-scale applications.

By combining AI models and GIS, the system analyzes weather impacts on whitefly populations, predicts risks, and provides targeted prevention strategies, such as optimizing pesticide use and crop management. This reduces crop damage, pesticide use, and environmental pollution while improving pest control efficiency and accuracy. The findings confirm that NB-IoT and MQTT-based solutions enable intelligent, data-driven pest management and are scalable for other pests and diseases. Future improvements aim to optimize system performance and broaden applications, supporting sustainable agricultural development with innovative solutions.

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