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IoT-based urban agriculture container farm design and implementation for localized produce supply

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ABSTRACT

With increasing population in cities, urban agriculture has been proposed as a solution for sustainable urban development and food security improvement. In this application note, as an attempt at small-scale controlled environment agriculture, a container farm was constructed to provide an anniversary localized fresh produce supply in urban areas. The constructed container farm adopted a multi-layer cultivation pattern with artificially controlled environment for maximizing revenue in limited urban vacant areas available. Considering requirements of efficient management, an internet of things (IoT) management system was designed to monitor and control environment of this container farm remotely and on-site. As a case study, the container farm was placed in an outdoor parking space for urban agriculture application with mushrooms as trial crop. The cultivation experimental results have shown that internal microclimate of the constructed container farm have presented the characteristics of long-term stability with short-term changes while the IoT system provided reliable production data collection.

1. Introduction

As densely populated assembly places, urban areas are requested as an uninterrupted supply of grains and fresh products to support normal life of the population requirements. According to an analysis of the World Population Prospects by the United Nations (United Nations, 2018), 55 % of the global population living in urban areas in 2018, which is projected to rise to 68 % in 2050. Expanding population puts enormous pressure on urban food security, due to most cities are consumers of resources, which almost completely rely on external supplies to satisfy grains, fruits, and vegetables demands (Pulighe and Lupia, 2020; Wu et al., 2022). In this situation, urban agriculture has been proposed to provide partially localized fresh food supplies, reduce transportation losses in long food supply chains, and promote food security and economic advancement in urban areas (Wielemaker et al., 2019).

Development of different forms of urban agriculture depends on the geographical location and urban construction planning as well as other conditions. Urban and community gardens are common forms of urban agriculture in developed countries, which have the dual role of serving both agricultural production and green landscape viewing (Song et al., 2022). However, land resources that can be utilized for agricultural activities are not readily available in cities with growing populations and vulnerable soils (Contesse et al., 2018). For achieving sustainable urban development, rooftop agriculture is seen as a kind of innovative practice for urban agriculture in compact cities with poor land resources and dense buildings. Challenges of rooftop agriculture include physical viability of existing buildings and limitations of fire regulations (Appolloni et al., 2021).

Constrained by limited land resources and changing climate, controlled environment agriculture (CEA) has been proposed to try out new developments in urban agriculture. Different from soil-based farming in rural, the urban CEA could deploy indoors and use soilless systems including hydroponics, aeroponics, and aquaponics (Gao et al., 2019; Zhang et al., 2022), etc. Interestingly, some miniaturized CEAs have shown great advantages in reducing up-front cost investment and shortening the distance between production sites and consumers. Developed as a new situation of miniaturized urban CEA, container

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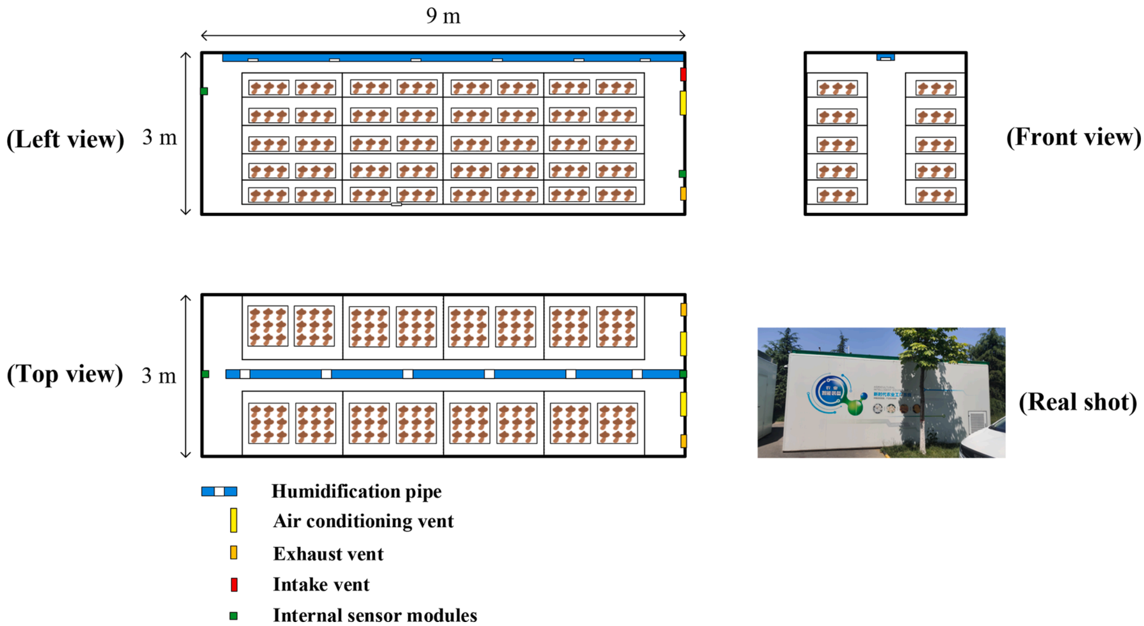


Fig. 1. Deployment schematic of the developed container farm.

farms have been paid particular attention, due to being easily deployable, maximizing space utilization with vertical layered planting structure, and transportable in urban areas (Liebman-Pelaez et al., 2021). Moreover, advancements in maximizing space utilization for container farms, which deploy vertically layered planting structures, are possible to reach more affordable in commercial farming applications (Martin

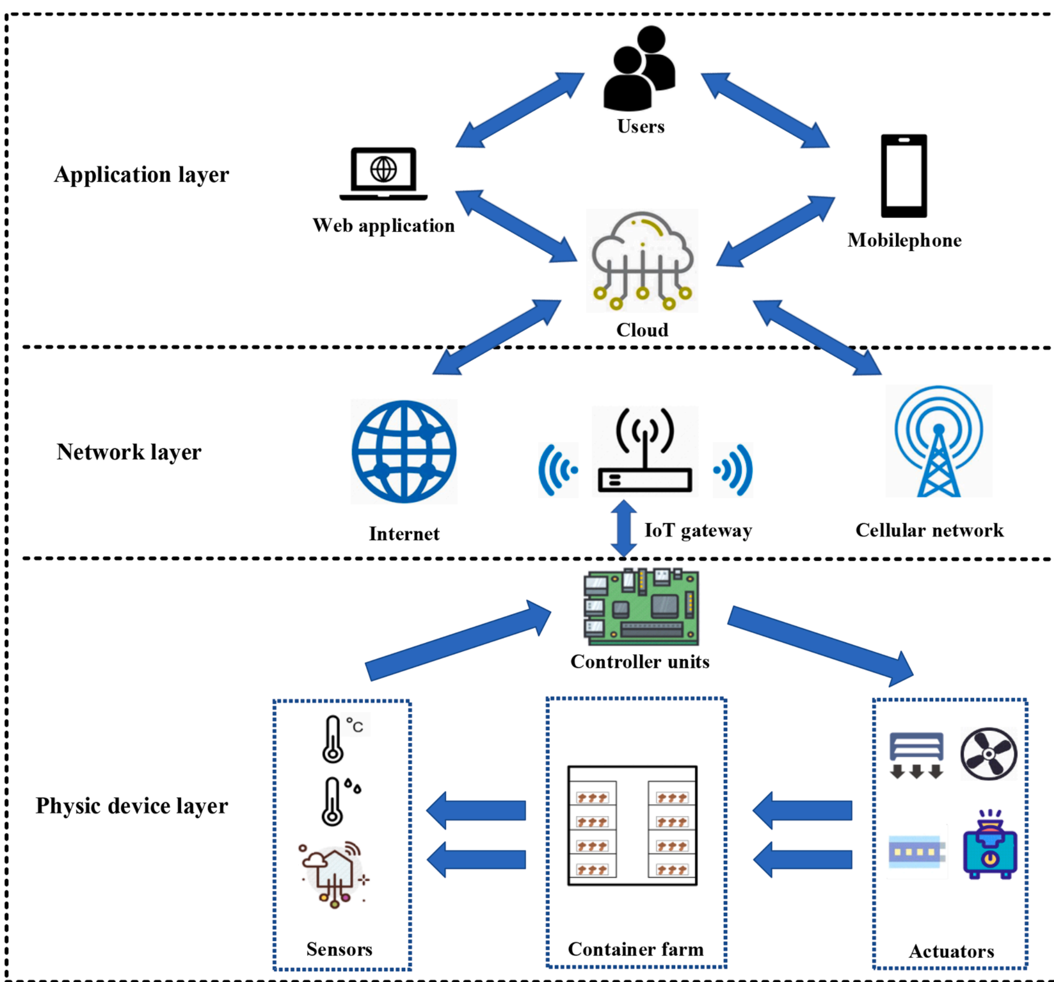


Fig. 2. Overall system architecture of the proposed IoT-based urban container farm.

and Molin, 2019).

Toward a high benefit CEA farming, efficient management that affects crop growth, quality and yield plays a critical role in sustainable production. As an extension of internet and sensor technology, the Internet of Things (IoT) has played an important role in the agricultural field and provided great benefits in many applications. Kim et al. (2020) reported a review of application of IoT for agriculture automation, which indicated that IoT is expected to increase crop quality and production while reducing resources inputs. Currently, IoT combined with remote control technology make contributes to reduce labor operations in agriculture production, such as growth monitoring (Harun et al., 2019), environmental regulation (Li et al., 2021), intelligent irrigation (Muangprathub et al., 2019), etc.

In this application note, an environment controllable container farm with a IoT management system was designed for urban agriculture application. All data collected by the IoT system will be stored in a cloud platform for later data mining to optimize control strategy and reduce energy inputs. The designed container farm was placed in outdoor parking spaces for trial cultivation of mushrooms and evaluated its feasibility.

2. Materials and methods

2.1. Developed container farm description

For the experiments, two container farms were constructed for urban food production with mushroom as trial crops. Both of these two container farms were constructed of sturdy aluminum alloy sheets with polyurethane thermal insulation interlayer, which were designed to enable working on adversities environment. Fig. 1 showed the design and deployment simplified schematic of the proposed container farm with internal dimensions of 9 m × 3 m × 3 m. In order to maximize space utilization, a multi-layer cultivation pattern was deployed to the proposed container farms. For these container farms, it only needs to provide reliable electricity and water that allows the basic function of mushroom crops cultivation and production in urban areas.

2.2. IoT management system design

An IoT management system was designed for the developed container farm to monitor and control internal environmental variables while recording production information. Fig. 2 showed the overall conceptual structure of the proposed IoT management system in this study. The system is divided into a three-layered structure, which includes a physical device layer for climate information perception and internal environmental regulation, a network layer for internet connection and information transfer, and an application layer for remote control command issuance and information management.

2.2.1. Physic device layer

For the constructed IoT management system, the physis device layer was proposed as collection of environmental information perception devices and internal environmental regulation devices. The physic device layer of this IoT management system is divided to multiple modules according to different system functional requirements.

(1) Sensor modules

Sensor modules in this system were divided into external installation sensor module and internal installation module. The external installation sensor module used in this study is a commercial product, called integrated outdoor weather station (JXCT, Weihai, China), which was installed on the top of the container farm shell to record the external data of air temperature and humidity, CO_2 concentration, and illuminance.

In this study, an internal installation sensor module was designed as a simple microcontroller that hosts a collection of two types of sensors. The functional block diagram of internal installation sensor module was shown in Fig. 3. An internal sensor module includes a microcontroller unit (ATmega328P, Atmel, USA), a humidity and temperature sensor (SHT20, Sensirion, Switzerland), and a miniature CO_2 sensor (S8 0053, SenseAir, Sweden).

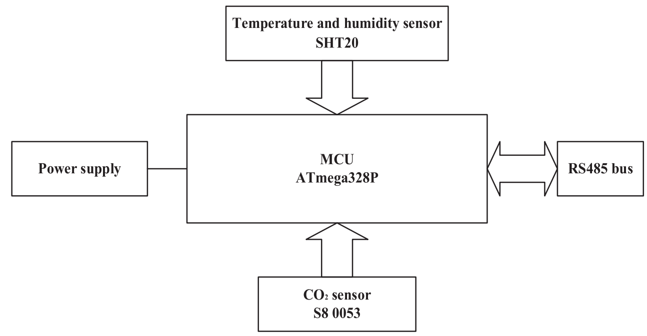


Fig. 3. The internal installation sensor module functional block diagram.

For the constructed container farm, an external sensor module was deployed at the top of case, and two internal sensor modules were deployed at different installation heights inside considering spatially microclimate differences in the container farm. Specifically, internal sensor module 1 and internal sensor module 2 were mounted on the upper and the lower of the container farm, respectively. The installation position, performance, and appearance of different sensors were listed in Table 1.

(2) Main controller

A self-designed main controller consist of ATmega2560 (Atmel, San Jose, USA) microcontroller and peripheral circuits was used to control and trigger the container farm internal actuators and transfer climate variables information. Its block diagram was shown in Fig. 4. The main controller in this study was designed as a two-layer structure in space, which includes the upper layer for information aggregation and control command issuance and the lower layer for internal environmental regulation actuators drive. For the upper layer, a universal control board was designed with clock circuits, USB-Micro program downloads interface, I/O interface, and communication interface, etc. Additionally, a JLX12864G LCD display was adopted to connect with the microcontroller via SPI for system commissioning information display. For the lower layer, eight solid state relay outputs channels (G3MB-202P, OMRON, Japan) were designed to trigger environmental regulation actuators with a CT357C optical coupler adopted to prevent an electrical collision and enhance anti-interference effect.

(3) Environmental regulation actuators

In this proposed container farm, environmental regulation actuators were adopted to maintain necessary environmental conditions including temperature, humidity, and air quality for mushroom crops growth. An air conditioning unit consisting of compressor and condenser was deployed for internal cooling while an electric heating component was installed at the bottom of the container for heating, which enable to achieve temperature regulation. An internal circulation fan was used for air agitation to achieve environmental zone balance. Crop growth lights were utilized as artificially controllable light sources to induce fruiting body differentiation during mushroom crops cultivation periods. A total heat exchanger with integrated energy recovery and ventilation was applied for container farm gas exchange between external and internal. An ultrasonic humidifier was utilized for producing mist while spread via a humidification pipe for container farm internal humidification. Except crop growth lights were driven by designed light controller, other

Table 1
Parameters and performance of internal installation and external installation sensors.

Installation position	Sensor	Type	Power supply	Measurement range	Performance	Appearance package
Internal installation	Miniature CO_2 Sensor	S8 0053	4.5 ~ 5.25 V	400 ~ 2000 ppm (Typical) 0 ~ 10000 ppm (Extend)	± 40 ppm	
	Humidity and Temperature Sensor	SHT20	2.1 ~ 3.6 V	0 % ~ 100 % RH −40℃ ~ 125℃	± 3 % RH ± 0.3℃	
External installation	Integrated Outdoor Weather Station	–	9 ~ 24 V	0 % ~ 100 % RH −40℃ ~ 80℃ 0 ~ 2000 ppm 0 ~ 200000 Lux	± 3 % RH ± 0.5℃ ± 50 ppm ± 7 % Lux	

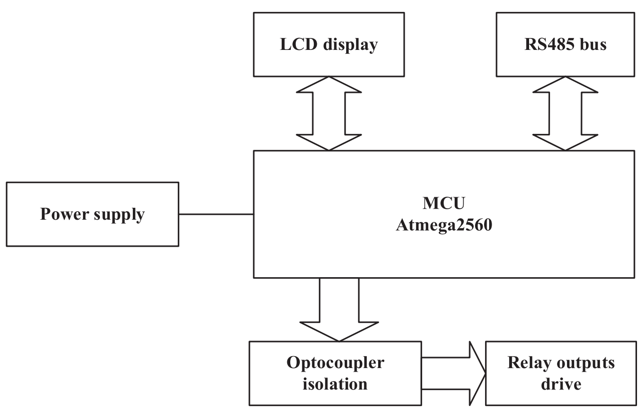


Fig. 4. The main controller functional block diagram.

Table 2
Related parameters of environmental regulation actuators.

Actuators	Power supply (V)	Rated power (W)	Function
Electric heating component	220	3000	Heating
Air conditioning units	380	4500	Cooling
Ultrasonic humdifier	220	1000	Humidification
Tatal heat exchanger	220	200	Ventilation, Energy recycle
Internal circulation fan	220	200	Air agitation

actuators were all triggered by relay outputs of the designed main controller. Relevant parameters of environmental regulation actuators mentioned above were shown in Table 2.

(4) Light controller

Same as the designed main controller, the self-designed light controller adopted a two-layer structure in space too. Its block diagram was shown in Fig. 5. For the upper layer, a universal control board adopted an ATmega328P microcontroller as control core was designed with clock circuits, USB-Micro program download interface, I/O interface, and communication interface, etc. For the lower layer, four pulse width modulation (PWM) light intensity adjustment channels were designed for artificial light actuation and control. In detail, each channel adopted a MOC 3052 (ON, Phoenix, USA) random-phase optoisolators triac for light intensity adjustment via changing the voltage conduction angle while achieving isolation of logic levels and AC voltages.

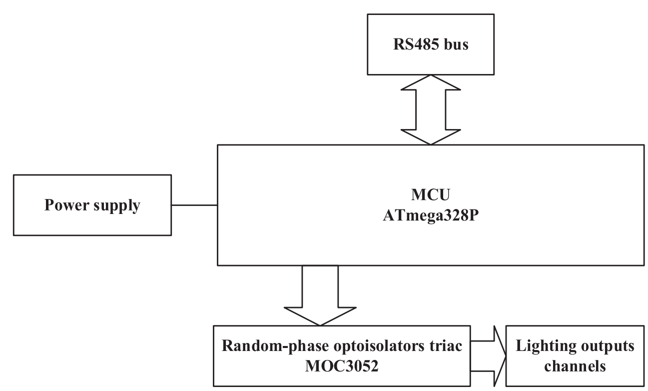


Fig. 5. The light controller functional block diagram.

(5) Communication bus

The physic device layer hardware of this system adopted a modular design, in which all sub-modules were connected to the main controller via a serial data bus for data communication. Considering system requirements of wiring and multipoint communication, RS-485 (EIA-485) was utilized as communication bus. All modules were equipped with a converter based on a MAX485ESA chip (Maxim, California, USA) for electrical level shift between UART/USART and RS485.

2.2.2. *Network layer*

As given in Fig. 2, the network layer was constructed for data communication between physical device layer and application layer. For the network layer, there are multiple protocols are used to enable communication in context layers, which include Bluetooth, Wi-Fi, and cellular networks, etc. The container farm is a new application of miniaturized CEAs, which requires fewer sensors and space occupation than traditional greenhouse. Therefore, a robust wired connection solution was applied for communication between physical layer and network layer. For the communication connection of network layer and application layer, 4G LTE cellular network was applied for remote data transportation while a wiring internet connection scheme was considered when the container farm was deployed at poor network signals areas in cities such as underground garages. In this study, the interface for connecting physical device layer and application layer is implemented via an internet gateway (SC-GN2280, SCICALA, China), which

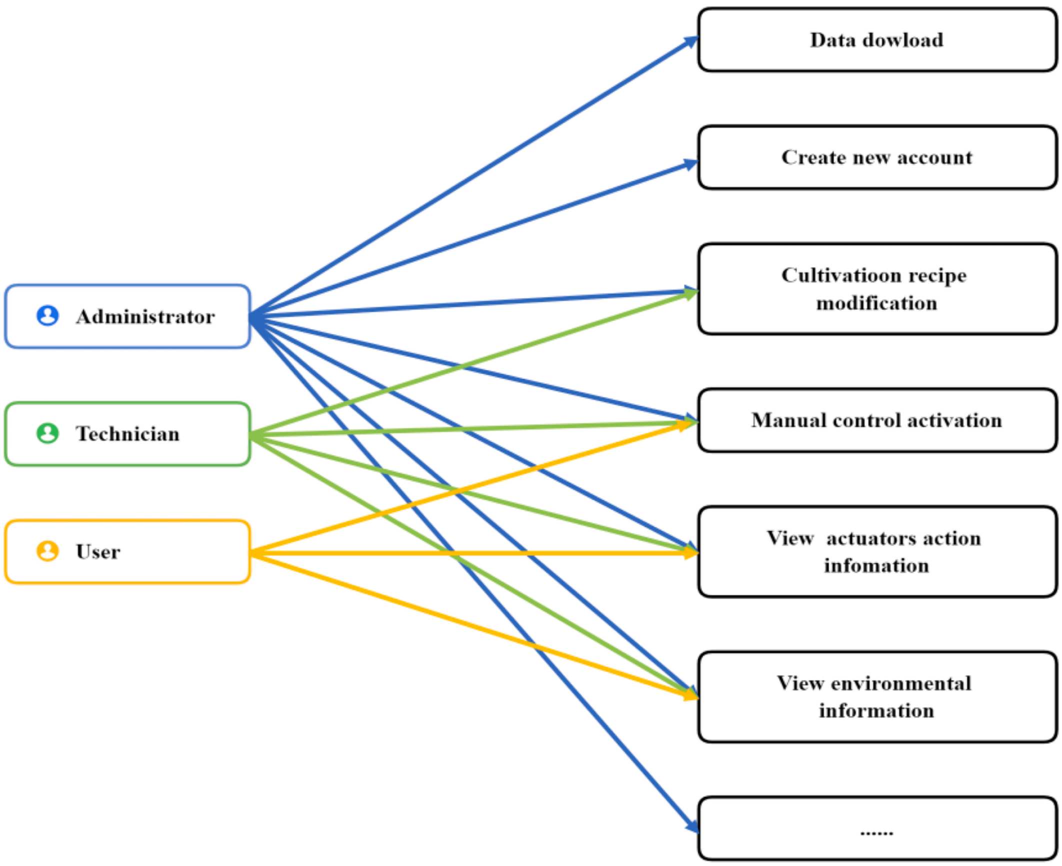


Fig. 6. Case diagram to show the available function of management accounts with different permission.

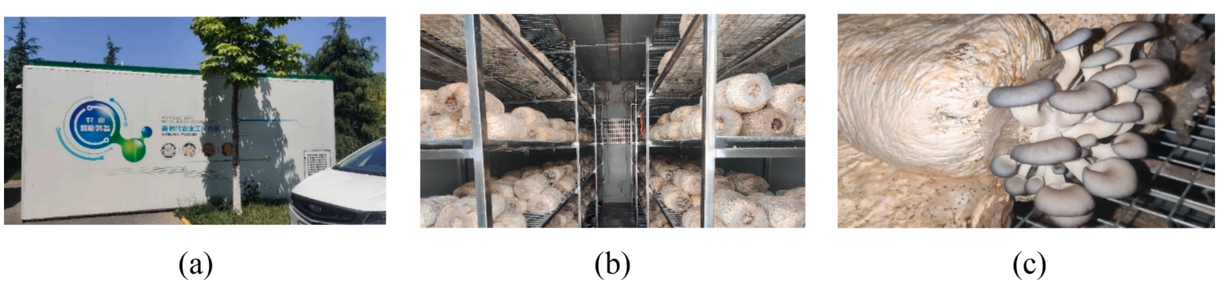


Fig. 7. Real constructed container farms for crops trial cultivation in an urban ground parking. (a) An exterior view of the constructed container farms. (b) An interior view of the constructed container farms. (c) Details scene of trial mushroom crops in cultivation.

provides network connectivity control functions and connectivity for data transporting.

2.2.3. Application layer

As the cloud-based backend that allows data storage and analysis, the application layer is an interface between system and user. In this study, the established IoT system was based on the SCICALA cloud platform (SCICALA, Shanghai, China). The platform allows data visualization while enabling remote controlling through provided application programming interfaces (APIs). In addition, all data were also stored as spreadsheets in the cloud, which can be downloaded from multiple terminals for data analysis and mining as long as the users have a system management account with specified permissions. In this container farm application, management accounts of the IoT system were divided into three types of administrators, technicians and users according to different functional permissions. A case diagram of permissions as shown in Fig. 6, which presented the example available functions of different management accounts.

3. Experimental results and discussion

3.1. Implementation of the designed container farm

As mentioned before, there were two container farms were constructed for urban crops trial production. These container farms were implemented as experimental urban CEAs with mushroom crops as trial crops, which were placed at a ground parking area in Yangling Industrial Park with geographical coordinates 34′28′’ N, 108′11′’ E. The ground parking areas provide reliable electricity and water supply for constructed farms production, and real views of deployment were shown in Fig. 7. A spatially multi-layered cultivating structure was adopted in constructed container farms that can be seen in Fig. 7(b), which greatly improved yield per unit area and space utilization. Fig. 7(c) showed the real shot of the trial mushroom crop in cultivation.

All measured environmental variable information from sensor modules were recorded on the cloud in real time via networks (4G cellular network and Internet network). Example real-time data

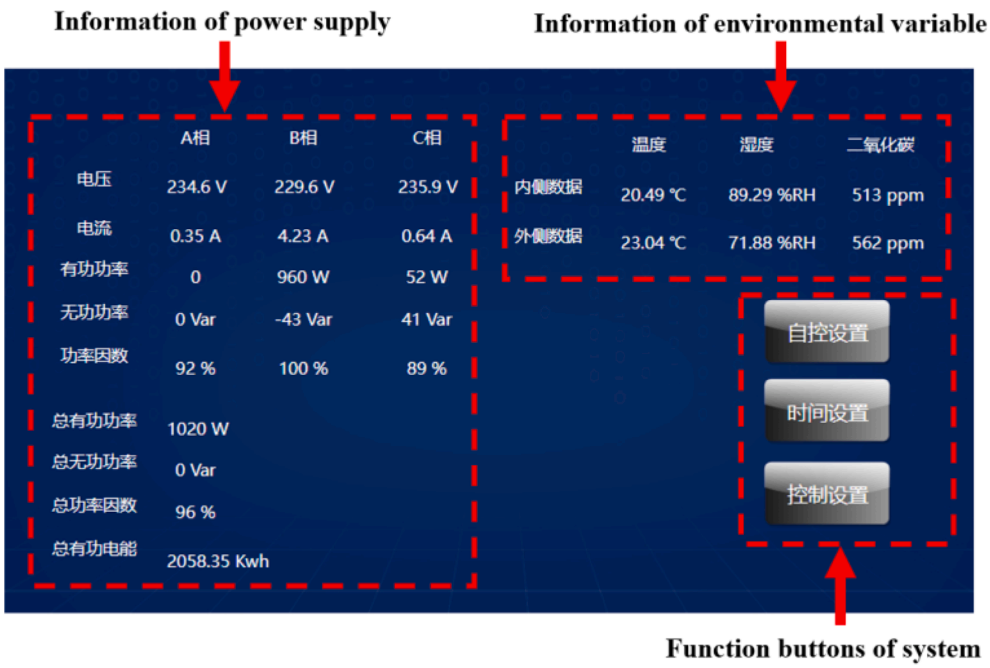


Fig. 8. Example visualization web windows for environmental variable information monitor.

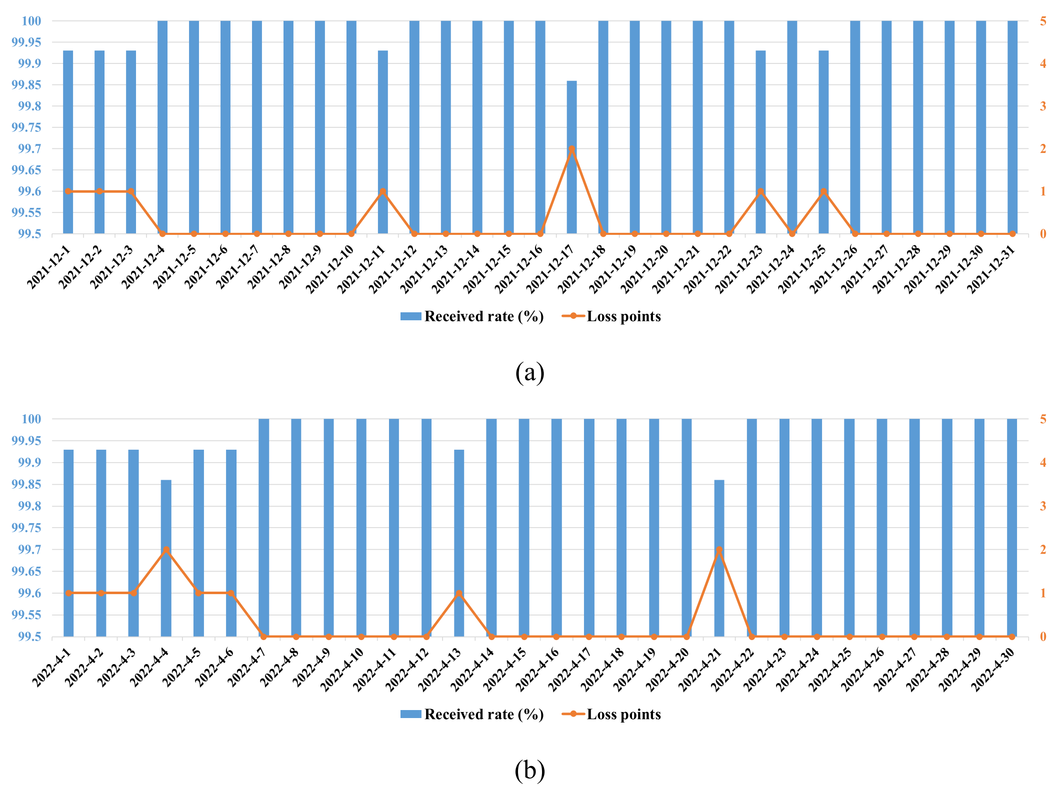


Fig. 9. Loss data points and received data rate. (a) Data from December 2021. (b) Data from April 2022.

visualization web windows were shown in Fig. 8, which presented the internal environmental variable information of sensor modules from one of the constructed container farms.

3.2. Performance validation of the designed container farm

3.2.1. Data transmission stability evaluation

For evaluating the proposed miniaturized urban CEAs performance, each one of the container farms has been in production since November 2021 with one minute as time interval for data collection. Ideally, there are 1440 data points that should be saved and recorded every day. Fig. 9

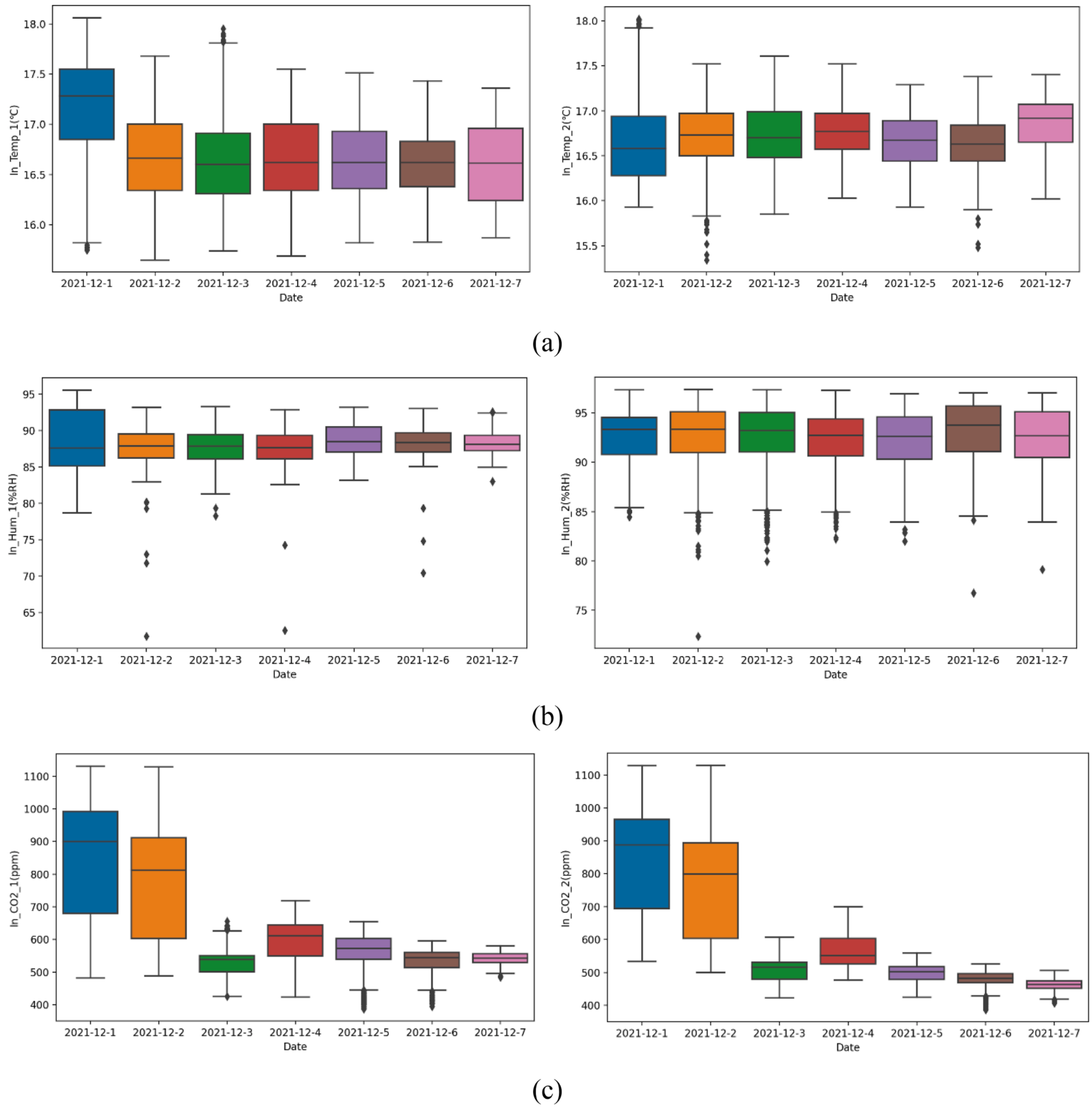


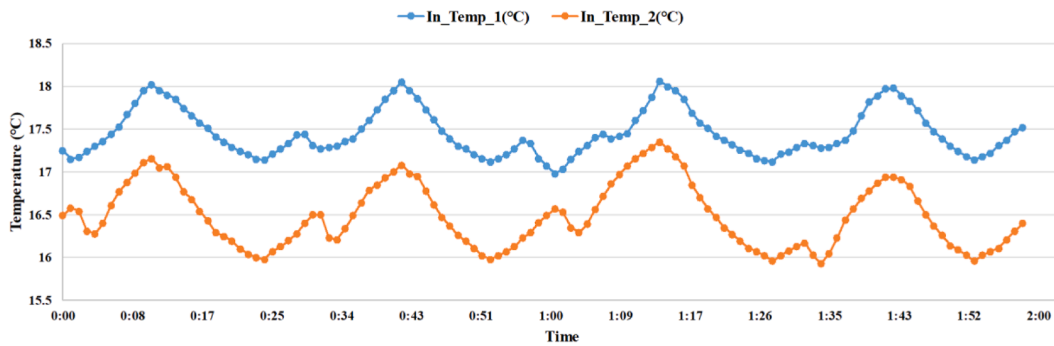
Fig. 10. The boxplot of container farm internal environmental variables. (a) Temperature (℃); (b) Humidity (% RH); (c) CO_2 (ppm).

showed the performance of data transmission stability for the designed system, with December 2021 as the winter representative month and April 2022 as the spring representative month. In this figure, received rate was applied to evaluate data transmission stability and the number of loss points per day was given too. Received rate was over 99.8 % and the number of loss points was less than 3 points per day for winter representing month (December) and spring representing month (April). According to the experimental results, the robust wired bus connection utilized for the physical device layer of this study has provided powerful support for data transmission.

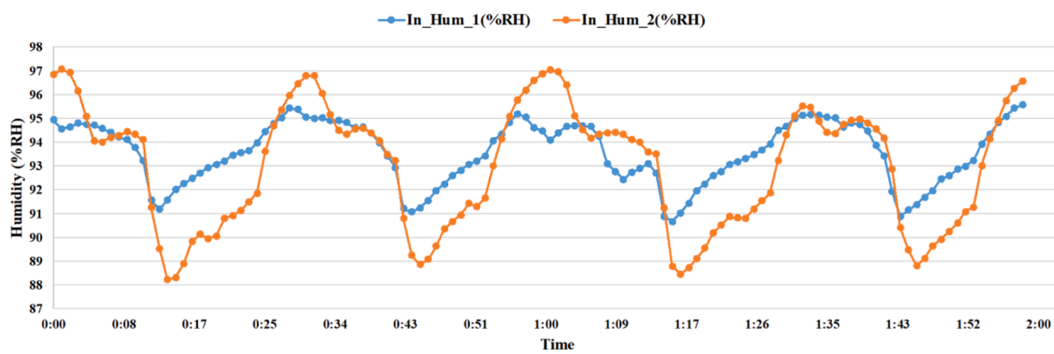
3.2.2. *Container farms internal microclimate stability evaluation*

An important task of CEAs is maintaining a stable internal environment during crops cultivation. Fig. 10 showed the internal environmental parameters of constructed container farm in the first week of December 2021, from which Fig. 10(a), Fig. 10(b), and Fig. 10(c) represented the temperature, humidity, and CO_2 content, respectively. The temperature data were marked as 'In_Temp_1′ and 'In_Temp_2′ depending on whether it was collected from internal sensor module 1 or internal sensor module 2. The same nomenclature was applied to humidity and CO_2 data too. Additionally, Fig. 11 showed the trend of environmental parameters inside the container farm in the first two hours of 1 December 2021, which contained a total of 120 data points for presentation.

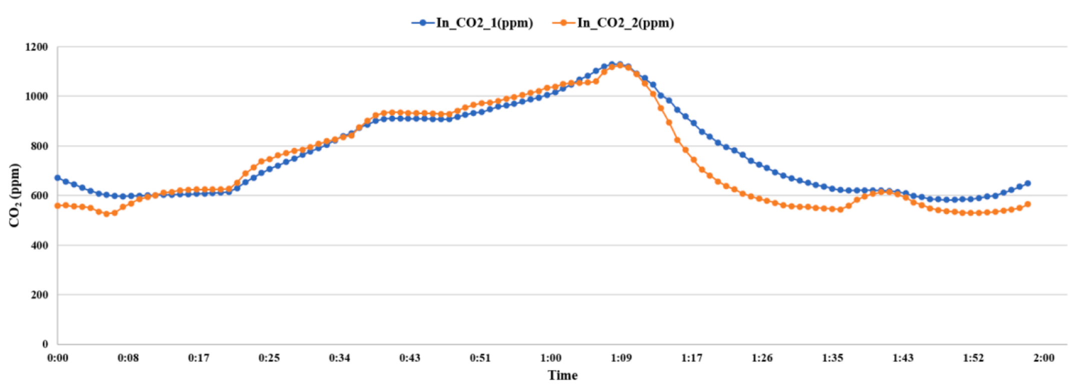
Environmental variables from recorded data presented the characteristics of long-term stability with short-term dynamic changes. As shown in Fig. 10(a), the average internal temperature of constructed container farm was controlled to between 16.5℃ and 17.5℃ with a dynamic stability range at approximately 16℃ to 18℃. The average internal humidity monitored by internal sensor module 1 and internal sensor module 2 was between 85 % and 90 % RH and 90 % to 95 % RH, respectively, as shown in Fig. 10(b). Fig. 11(a) and Fig. 11(b) showed change of internal temperature and humidity in two hours, which presented a typical cyclical fluctuation as actuators turning on and turning off. Due to mushroom crop respiration and the effects of moist air sinking, the temperature monitored from internal sensor module 1 (the



(a)



(b)



(c)

Fig. 11. Internal parameters from two sensor modules monitoring in the trend graph. (a) Temperature (°C). (b) Humidity (% RH). (c) CO_2 (ppm).

upper parts of container) were higher than that from internal sensor module 2 (the lower parts of container) normally. Air humidity of container farm has a wider fluctuation range in its lower part due to the dual effects of ventilation and humid air deposition.

As shown in Fig. 10(c), the content of CO_2 in the first two days were controlled approximately between 500 and 1140 ppm and other days were approximately between 400 and 700 ppm. During the selected period, experimental mushroom crops were in the transition stage from mycelium to fruiting body. Set environmental parameters in cultivation recipe were different between the two growing periods. In the life cycle of mushrooms, the aeration requirements are more stringent in fruiting body development phase than in mycelial phase because of its greater demand for oxygen. Additionally, there are a few discrete points as shown in Fig. 10, which are identified as outliers in these boxplots. According to the system log records, door opening operations that damaged the farm relative airtightness and wrong manual operations of actuators caused fluctuations in the internal environment of the container farm, which were the main reason for these outliers. In general, the constructed container farm can meet the requirements of urban crop production and has good stability.

4. Conclusion

The continuous expansion of urban areas and increase of population have put forward higher requirements for uninterrupted supply of fresh produce. For this application note, a container farm as miniaturized CEA was designed and implemented for urban agriculture application to provide localized fresh produce supply. An IoT-based management system was designed able to monitor and control environment of this container farm remotely and on-site, allowing information storage as well as download for data mining. Actual cultivating experiments showed that the implemented container farm could meet requirements for urban agriculture production with convenience in management and maintenance. However, long-term production experiments are still required to provide data support for improving the urban CEA structure optimization and its control system design.

CRediT authorship contribution statement

Leilei He: Data curation, Investigation, Methodology, Writing – original draft. **Longsheng Fu:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Wentai Fang:** Conceptualization, Methodology, Writing – review & editing. **Xiaoming Sun:** Conceptualization, Methodology, Writing – review & editing. **Rui Suo:** Conceptualization, Methodology, Writing – review & editing. **Guo Li:** Conceptualization, Methodology, Writing – review & editing. **Guanao Zhao:** Methodology, Supervision, Writing – review & editing. **Ruizhe Yang:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Rui Li:** Methodology, Data curation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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