Towards Automated Greenhouse: A State of the Art Review on Greenhouse Monitoring Methods and Technologies Based on Internet of Things

Haixia Li[a,b,c,1], Yu Guo[a,b,c,1], Huajian Zhao[a,b,c,1], **Yang Wang**[a,b,c*], David Chow[d]

a) College of Information and Electrical Engineering, China Agricultural University, 100083, Beijing, China

b) National Innovation Center for Digital Fishery, China Agricultural University, 100083, Beijing, China

c) Beijing Engineering and Technology Research Center for Internet of Things in Agriculture, China Agricultural University, 100083, Beijing, China

d) School of Architecture, University of Liverpool, L69 7ZN, Liverpool, UK

[1]: H.X. Li, Yu Guo and H.J. Zhao contributed equally to this work. [*]: Author to whom all correspondence should be addressed.

Address: College of Information and Electrical Engineering, China Agricultural University, 100083, Beijing, China;

Email addresses andy_yangwang@cau.edu.cn, wanghongyang1767@gmail.com (Dr. Yang Wang)

Abstract

As a controllable environment, greenhouse has less resource consumption and emission than field crop production and reduced greenhouse gas emissions from agricultural production. Besides, the greenhouse with an intelligent monitoring system has better energy-saving and emission reduction effects. Simultaneously, the intelligent monitoring system can predict the extreme greenhouse environment in advance, reduce diseases and insect pests, reduce the use of pesticides and fertilizers, and provide high-quality food. Researchers are becoming more and more interested in greenhouse monitoring systems, and how to put them into production correctly and effectively is a major challenge. This paper aims to review the intelligent greenhouse monitoring system systematically, serve the data transmission and server processing subsystems by identifying, listing and further explaining the greenhouse environmental parameters and studying the overall design of the greenhouse monitoring system. According to the characteristics of each component of the system, the paper makes a comparative study and obtains its development trend, summarizes the current popular technology and the future development trend of the intelligent monitoring system, and provides support for the research of greenhouse monitoring system. It was found that multi-parameter monitoring is beneficial to achieve effective greenhouse control, and wireless technology has gradually replaced wired mode for data transmission in the environment both inside and outside the greenhouse. Notably, deep learning, big data, and other advanced technologies used in greenhouse monitoring are considered valuable developments, further refine unmanned greenhouse management, and further improve greenhouse construction's energy utilization.

Keywords: Agriculture greenhouse building; Environment; Energy saving; Internet of Things (IoT); Monitoring system

Contents

1. Introduction

Greenhouse gas emissions from agricultural production account for 30% of greenhouse gas emissions from human activities[1]. Therefore, it is crucial and urgent to improve agricultural resource consumption and resource recycling and reduce emissions[2]. The greenhouse has become an essential building in agricultural production. As a controllable environmental agricultural facility, the greenhouse can effectively promote crop metabolism, control diseases and pests[3], improve resource utilization, and reduce environmental pollution and carbon emissions[4].

Greenhouse construction management is a multi-factor optimization problem that affects crop yield and resource utilization efficiency of land, water, and energy. Efficient greenhouse systems play a crucial role in sustainable production. To solve this problem, Liu et al. proposed to use monitoring system to monitor the greenhouse environment in greenhouses[5]. The monitoring system includes sensor monitoring network for environment data acquisition, a special sink node to gather data and send back to the remote management center based on communication network.

A greenhouse monitoring system can control and maintain the greenhouse environment, such as increasing light, improving plants' photosynthesis, and improving plants' growth rate. The systems can continuously obtain real-time data, reduce the use of pesticides, reduce human input, and reduce energy and resource consumption in greenhouses, thereby maximizing production yield and quality[6–9], and preventing damage to crops by extreme environments.

Studies have shown that compared with average growth, tomatoes' growth rate in the automated greenhouse based on the Internet of Things (IoT) monitoring system is twice as fast[10,11]. Keeping environmental factors such as temperature and humidity at a certain level can improve the quality and yield of plants and save resources. Azaza et al. prove that using the greenhouse IoT monitoring and control system to control temperature and humidity at specified levels can reduce energy consumption by about 25% and water consumption by 33%[12]. Also, the monitoring system with an intelligent decision module can effectively improve the decision-making ability and reduce the loss caused by misjudgment[13].

In the past 20 years, scientists worldwide have researched the greenhouse monitoring system, formed many beneficial achievements, carried out practice in agricultural production, and brought progress [9-12, 14-16]. Reyes et al. focuses on the study of environmental factors and found that environmental factors are critical to greenhouse monitoring systems[14]. However, few scientists have reviewed the overall design of the greenhouse monitoring system including greenhouse environment awareness, data communication and server information processing subsystems.

Aasthi et al. discussed the basic communication principle of data transmission and the topology diagram of sensor nodes in the greenhouse monitoring system based on ZigBee and GSM to realize the ad-hoc network of dynamic clustering among nodes[15]. Tzounis et al. focused on studying the future and research trend of the current greenhouse monitoring system and found that the convenience of greenhouse management brought by the greenhouse monitoring system was the biggest advantage in the future, while the security should be considered in the future[16].

As mentioned above, it is understandable that the review paper on greenhouse monitoring system has explored the application, importance, environmental factors, sensor node topology, research trends, and other elements of greenhouse monitoring system as the cornerstone of the study of greenhouse monitoring system. However, which parameters need to be monitored? What is the overall structure of the system? What technologies should be used for each part of the system? What are the advantages and disadvantages of different technologies? These problems have not been thoroughly investigated, which makes most of the practice of greenhouse monitoring system stay in the laboratory rather than put into production. Therefore, writing this review, we hope to introduce the development trend of greenhouse monitoring technology, define the greenhouse monitoring system's evaluation criteria, and make guidelines for designing the greenhouse monitoring system. Simultaneously, based on the challenges and problems proposed by Tzounis et al. [16], this paper gives some solutions. In Section 2 of this paper, the methods are introduced firstly, including the literature retrieval and a brief description of the greenhouse monitoring system. Section 3 presents the research results, including the significance of greenhouse monitoring, environmental awareness subsystem, data communication subsystem, and server information processing subsystem. Section 4 is the discussion of existing greenhouse monitoring system limitations, challenges and research gaps. Finally, Section 5 summarizes and prospects the whole paper.

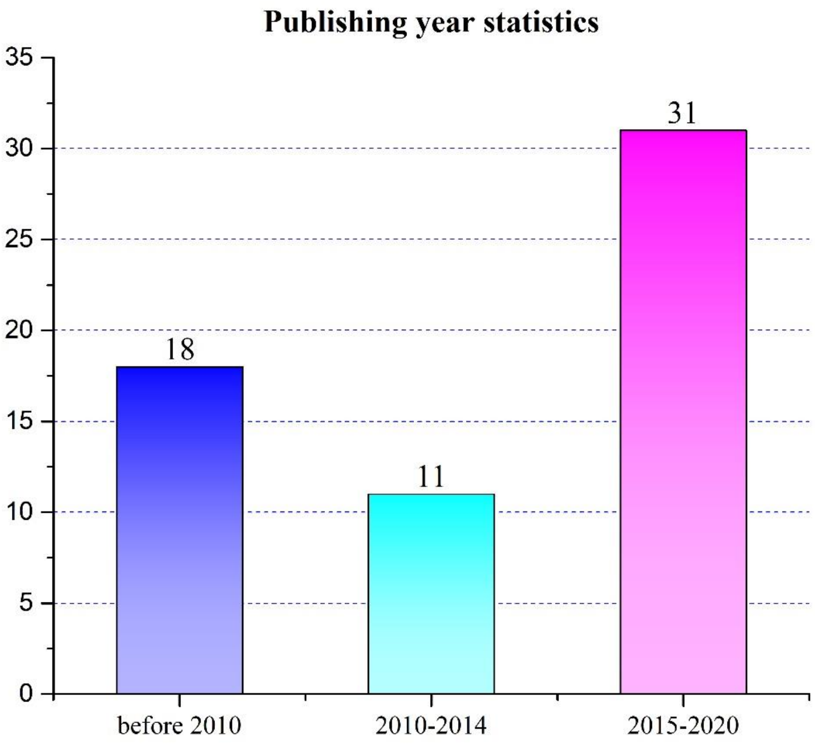
2. Method

2.1. Literature Retrieval

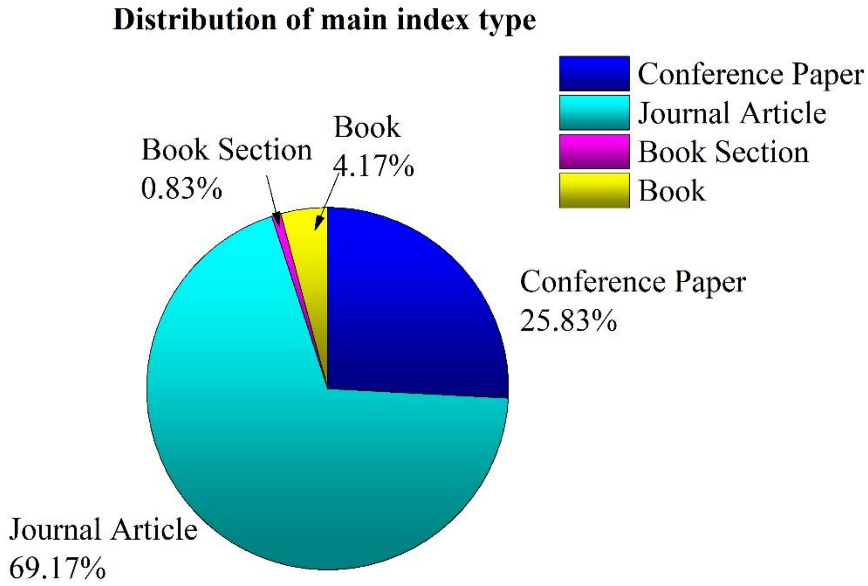
The literature selected in this study is mainly from the following databases: Web of Science, Science Direct, IEEE, and Google Scholar. Select the keywords for evaluation and determine the relevant scientific papers, including three categories: "greenhouse -", "monitoring", and "environmental efficiency".

The publication date of the selected literature in this work is limited to the last 25 years, from 1996 to 2020. These studies focus on the use of intelligent monitoring systems in agricultural greenhouse production. According to the above keyword criteria and publication time, correlation analysis, and screening, and up to 107 articles (main findings as demonstrated in Tables A.1, B.1 and C.1) were screened out and further reviewed.

Fig.1 (a) and (b) show the year statistics and distribution of the selected papers' main index journals. It can be seen from Fig.1 (a) that in the past five years, more and more attention has been paid to the research of intelligent greenhouse monitoring system. According to Fig. 1 (b), journal article accounts for the largest proportion of articles related to the above research, accounting for 69.17%.


Publishing year statistics
35
30
25
20
15
10
5
0
18
11
31
before 2010
2010-2014
2015-2020

(a)


Distribution of main index type
Conference Paper
Journal Article
Book Section
Book
Book Section
0.83%
Book
4.17%
Conference Paper
25.83%
Journal Article
69.17%

(b)

Fig. 1. Publishing year statistics (a) and distribution of main index type (b) for those selected articles in this work.

2.2. Overview of The Greenhouse Monitoring System

According to the literature review [108-111], the greenhouse monitoring system structure (see Fig. 2) includes three subsystems: (1) monitoring subsystem in the greenhouse for environmental perception, i.e, environmental awareness subsystem, which can monitor the greenhouse environment and crop parameters and acquire those monitoring data, (2) information processing subsystem for a server to calculate perceived information, i.e., server information processing subsystem, which can store, analyze and visualize monitoring data and then make a decision and (3) communication subsystem for data exchange between the two subsystems mentioned above, i.e., data communication subsystem, which can communicate the data, process the signal and control the actuator.

As illustrated in Fig. 2, it clearly indicates greenhouse IoT subsystem function and correlation. There are three subsystems including environmental awareness subsystem, data communication subsystem and server information processing subsystem. The environmental awareness subsystem includes environment, crops and soil sensors, which can acquire monitoring data. The functions of data communication subsystem cover signal processing, control actuator, node network and data communication. Server information processing subsystem can deal with data storage, query and visualization; make the intelligent decision and control; proceed the intelligent early-warning, equipment and authority management.

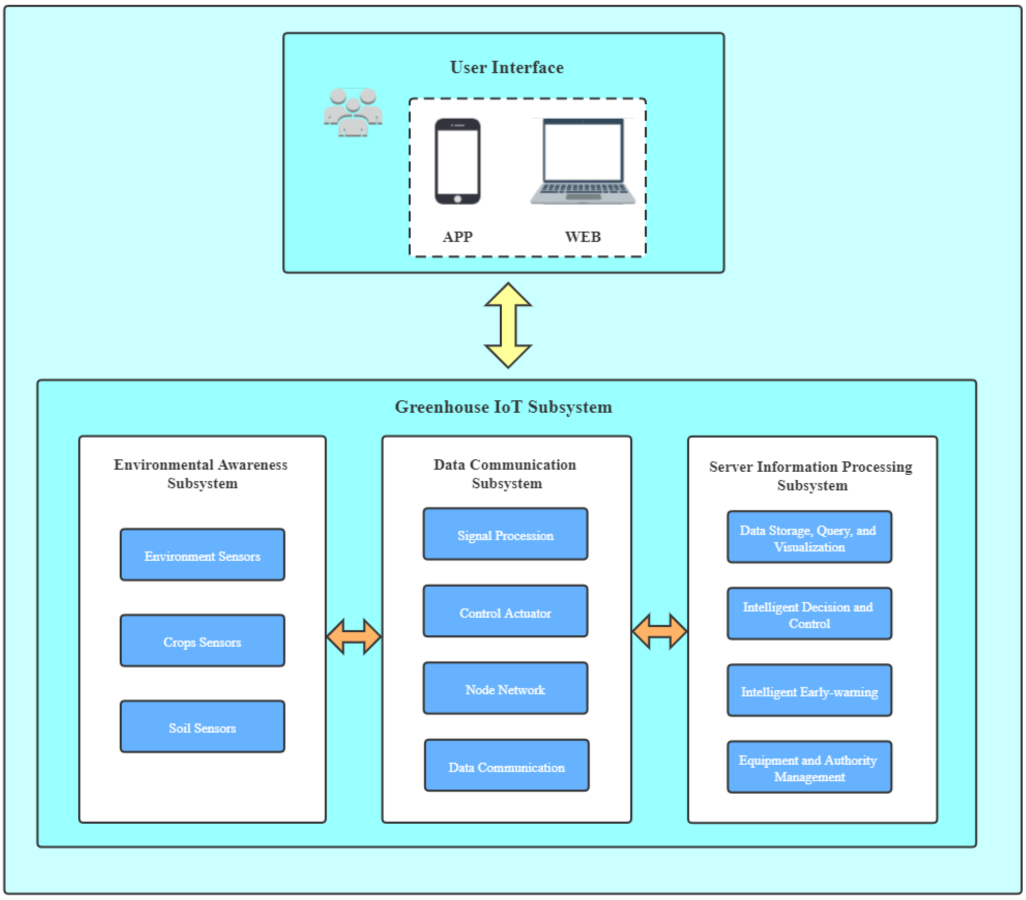


Fig 2. Subsystem functions and correlation diagrams

3. Results

This section will systematically review greenhouse monitoring methods and technologies based on internet of things considering monitoring system structure, i.e., environmental awareness subsystem, data communication subsystem and server information processing subsystem. The detailed contents are demonstrated in Table 1.

Table 1 Greenhouse monitoring system structure and review contents

Subsystem	Review contents
Environmental awareness	*Monitoring Parameter*: Air temperature & relative humidity, CO_2%, light, soil

	temperature & humidity, leaf temperature and humidity
Data communication	*Slave computer*: microcomputer, Arduino, TelosB Platform, Raspberry Pi; *IoT communication protocol*: wired mode, wireless mode: Zigbee, LoRa, NB-IoT, Wi-Fi, Bluetooth, Private protocols *Communication protocal between greenhouse and server*
Server information processing	

3.1. Environmental Awareness Subsystem

The production system is continuously monitored and precisely controlled. In these highly computerized and automated systems, the quality of the information provided by sensors and decisions transmitted to actuators is essential. High-quality and effective data reduces errors during data transmission and improves the visualization and decision-making quality of information processing on the server.

Plant growth quality and yield are affected by various environmental factors. Continuous monitoring of these environmental parameters provides valuable information for growers to better understand how each factor affects plant quality and growth rate as well as maximizes crop yield. The sensing subsystem in the greenhouse includes sensors for environmental monitoring.

Greenhouse crop is greatly affected by the surrounding environment. The traditional greenhouse monitoring system mainly monitors the greenhouse environmental data, such as environmental temperature and relative humidity. Using the monitoring system's greenhouse environmental data can control the indoor environment more effectively and reveal various related crop yield factors.

The main factors affecting plant growth are environmental temperature, environment relative humidity, light, soil moisture, and carbon dioxide (CO_2) content[17]. In addition, the above five parameters are interdependent[20,21]. The greenhouse's internal environment is relatively closed, but the internal environmental parameters are coupled[20]. Thus, the greenhouse is a complex, nonlinear, and strong coupling system[21]. In the past 20 years, the monitoring of crop physiological status has also been included in the greenhouse environmental monitoring, so it is necessary to monitor the crop status.

So far, there is no accurate physical model to determine the law between the parameters, and the mechanism model can not be used to transform and calculate the parameters. Therefore, it is necessary to analyze different greenhouse types and crop types to determine the required parameters and sensor types for monitoring. For the required parameters, the corresponding sensors must be used to monitor atomically. The relationship between them should be analyzed in various ways to establish the greenhouse environment model and find out the straightforward and formulaic relationship between the parameters.

3.1.1. Environmental Monitoring Parameters

The following section will focus on the significant greenhouse environmental parameters, which can obviously impact the crop growth and development as well as productivity, including environment temperature, relative humidity, CO_2%, light, soil temperature & humidity.

3.1.1.1. Environment Temperature

Environmental temperature is one of the most critical parameters that directly affect the growth of crops, and it has a significant impact on crop yield[22]. The unsuitable environmental temperature will affect the planting period of crops. If the ambient temperature is too high, the planting period of crops will shorten, which reduce the yield of crops[23–25], and accurate temperature control will significantly increase the yield. Simultaneously, the growth habit of crops also depends on the appropriate environmental temperature[24,26]. The environmental temperature has an impact not only on the yield but also on the quality of crops. At the same time, the temperature inside the greenhouse is also changeable[27]. The temperature inside the greenhouse will change with the change of time or season, and these changes will hinder the growth of crops[28].

The results show that the most significant impact on crop growth and metabolism is maintaining a constant temperature or maintaining the optimal temperature change range in the greenhouse. Through accurate monitoring and appropriate control, intelligent management of the greenhouse can be achieved[29].

3.1.1.2. Environment Relative Humidity

As high humidity rarely directly impacts plant growth, this climate parameter is often ignored as long as there is no disease. Nevertheless, in fact, environmental humidity is closely related to crop growth, volume, diseases, and insect pests.

The change in environmental humidity will lead to the change of crop biomass. Increasing the humidity may increase the leaf area and dry weight of agricultural plants[30–32]. Unsuitable environmental humidity will bring diseases to crops[33]. If the humidity is lower than a specific range, it will lead to plant water stress (PWS), which will reduce growth. High humidity can cause disease, which may lead to growth and development disorders. At some crop growth stages, it is necessary to increase the environmental humidity to prevent insect pests. In the experiment, when the air humidity is lower than the appropriate value, the mycelium will dry and wither; when the air humidity is higher than the appropriate value, the mycelium grows rapidly, but it is difficult to breathe[34]. At the same time, environmental humidity can also affect the physiological process of crops. The water consumption of plants growing under high humidity conditions is much higher than that of plants growing under low humidity conditions[31]. Besides, under high humidity conditions, the photosynthetic rate of plants decreased, and transpiration changed[35]. When the environmental humidity is too high, it will lead to gray mold and cause leaf wilting[31]. The microelements needed by crops are also closely related to environmental humidity. When plants grow at different air humidity levels, soil salinity in flowerpots is easy to change[26,32]. When vapour pressure deficits (VPD) decreased, the tomato leaf area decreased significantly, due to calcium deficiency[36]. The difference in the flowering period of plants is closely related to the humidity of the environment. High humidity may delay or advance the flowering period[37].

To achieve these goals: (1) better control the trace elements required by crops (2) reduce the probability of diseases of crops (3) achieve the control of physiological processes such as respiration and photosynthesis. It is indispensable to grasp and control the environmental humidity of crop growth. Studies have shown that strict control of environmental humidity has obvious effects on flowering phase adjustment in horticulture research, but it is not easy to control environmental humidity[38]. Besides, to decrease energy consumption and control CO_2 concentration, ventilation should be avoided to reduce humidity, so environmental humidity is essential and complex. The installation of environmental humidity sensor can immediately grasp the humidity situation in the greenhouse and achieve better control.

3.1.1.3. Carbon Dioxide Concentration

Carbon Dioxide/CO_2 is one of the essential raw materials for plant growth. If the concentration of CO_2 is appropriately increased, the rate of photosynthesis and the yield of crops will be increased[24,39–41]. Even a small amount of CO_2 can significantly increase crop yield[42]. As mentioned earlier, the increase in temperature will reduce crop yield, and higher CO_2 content can offset[23,24].

Increasing CO_2 concentration is an effective method to increase crop yield, but this method is expensive, and high CO_2 concentration may bring danger to farmers in the greenhouse. Therefore, we must master the greenhouse CO_2 concentration to keep it in a more appropriate range and balance cost, production, and safety.

3.1.1.4. Light

Light is an essential factor for the photosynthesis of crops. Marcelis et al. shown that an average 1% light gain can increase production by 0.5-1% for most crops[43], indicating that light positively impacts quality.

Light and other growth factors often affect the growth of crops. For different light intensities, there is a matching optimal air temperature to maximize the effect of photosynthesis. However, the optimal values of different plants are different[43,44]. Studies have shown that appropriate greenhouse temperature and light intensity can improve strawberries' yield and quality[45]. Some studies have also proved that the fruit production of yield and quality per plant of shaded strawberry is better than that of non-shading strawberry under the combined regulation of night heating and daytime shading[46]. Besides, the light duration is also an essential factor. Some studies have shown that the stem/root ratio increases with the increase of temperature and photoperiod[47]. For gardeners, plant morphology is essential. Studies have shown that light quality significantly affects the morphological changes of chrysanthemum, tomato, and lettuce[48].

Therefore, it is necessary to monitor the light intensity in the greenhouse to keep the light intensity at a certain level. When the weather is terrible and the light intensity is too low, it will send out a prompt message and turn on the fill light to supplement the lighting. In the cultivation of particular plants, appropriate shading treatment can be adopted.

3.1.1.5. Soil Temperature

The soil temperature is related to the greenhouse environment temperature but not wholly consistent. Moreover, the effect of soil temperature on crops is significant. Soil temperature will seriously affect the enzyme, trace elements, and growth of crops[49]. Xu et al. proved that the growth of cool-season grasses would be limited if the soil temperature is too high[50]. The appropriate temperature will improve the physiological function and yield of crops.

Licht et al. proved that increasing soil temperature promoted the increase of plant emergence rate index (ERI) under strip tillage[51]. Stone et al. proved that biomass and yield in the warmest soil temperature increased by 21% compared to maize grown in the coldest soil temperature[52]. However, if the temperature exceeds the experimental range, it often brings disease. With the increase in soil temperature, the disease chance increases obviously[53]. The resistance of tomato to Fusarium Wilt decreased significantly with the increase in soil temperature[54].

Water bath pipe is widely used in greenhouse to control soil temperature. The cost is high. Therefore, it is necessary to monitor the soil temperature, send out information at extreme temperatures, and start a water bath to control temperature and reduce cost accurately. Karim et al. developed a plant water stress warning system based on IoT, which can warn when soil water is insufficient[55].

3.1.1.6. Soil Humidity

Water diversion is the basis of biophysical processes to maintain ecosystem functions[56]. Hornick et al. proved the effect of soil humidity on crop quality[57]. At the same time, soil humidity controls canopy coverage, leaf area, transpiration, and community composition[58]. Besides, an ecosystem's biodiversity is significant for crop growth, and soil humidity content may affect species richness and distribution[59]. The higher the soil humidity content and atmospheric humidity are, the stronger the plant diversity will be [62].

Soil humidity, air temperature, and plant growth rate factors are different at different times of the year. In the greenhouse, it is not in contact with rainfall, and the way of manual drip irrigation is often adopted according to experience. As a result, plants can not get enough water at an appropriate time, leading to water shortage or even death of crops. Obtaining too much water will waste water resources, increase costs, and lead to plant root rot[60].

By monitoring soil humidity, we can provide corresponding information for greenhouse irrigation management[61]. When reaching the threshold value of soil humidity, the water supply will be provided accordingly. The user can track his crops from any remote location. Although users' not at the side, it still ensures plants' healthy growth and crop yield and quality[60].

As demonstrated in Table B.1, the previous studies indicate the most frequent monitoring greenhouse environment parameters investigated are temperature, relative humidity, light and CO_2 concentration.

3.1.2. Monitoring Crop Parameters

This section will concentrate on crop parameters monitored in the greenhouse, which includes two important factors leaf temperature and humidity. Both parameters can significantly influence greenhouse crop growth, development and metabolism.

3.1.2.1. Leaf Temperature

Crop growth and metabolism depend on crop temperature. Because crops are complex, leaf temperature is often used in experiments to represent crop temperature [62]. Suppose the temperature of leaves is too high or too low, the activities of enzymes related to photosynthesis will decrease, and photosynthesis will decline, which will finally affect plants' yield and quality[62]. Besides, the leaf temperature determines the concentration or pressure of water vapor in the leaves, so it determines the driving force of transpiration. The energy budget of leaves is closely related to photosynthetic rate and leaf temperature[63]. Studies have shown that indoor temperature and humidity are not necessarily the same as leaf temperature and humidity, so it is necessary to monitor plant leaves' temperature and humidity separately. Moreover, because the blade temperature changes are generally subtle, the sensor with higher accuracy is often used to measure the blade temperature[64].

3.1.2.2. Leaf Humidity

There is a specific correlation between indoor temperature and humidity and leaf temperature and humidity, but it does not equal. Park et al. have shown that when the greenhouse environment temperature is higher than the crop temperature and the relative humidity is too high, and the huge temperature difference will lead to the leaves' dewing and reduced transpiration [65]. Also, the dew on the leaves will lead to diseases. Korner et al. also proved the relationship between leaf surface temperature and transpiration[66]. The low VPD between environmental humidity and leaf humidity may lead to low transpiration and related physiological disorders, thus reducing crop growth. Plant diseases are also closely related to leaf surface humidity. A high humidity environment can easily lead to gray mold, leaf mold, and powdery mildew [67]. In general, it is essential to control the indoor environment and maintain the appropriate humidity range of leaves to cultivate healthy crops and prevent Fusarium Wilt and harmful fungal diseases.

Seen from Table B.1, there is no more studies to investigate monitoring greenhouse crop parameter than environmental parameters, however, leaf temperature and humidity are still valuable and significant for Crop growth and metabolism based on the aforementioned description.

3.2. Data Communication Subsystem

3.2.1. Slave Computer

With the continuous development of monitoring technology and the continuous improvement of greenhouse environmental monitoring requirements, the types and quantity of sensors in greenhouse monitoring systems are continually improving.

On the one hand, if each sensor directly connects to the server, it is not only expensive to add a remote data transmission function for each sensor individually, which will greatly increase the cost of the monitoring system, but also will increase the difficulty of management, and make it challenging to increase other sensors and equipment. On the other hand, it is cost-effective and unreliable for a server to work a long time to complete the simple sensor data acquisition task, reducing the flexibility of monitoring platform design[68].

The most popular solution is to use a microcomputer with a specific expansion and processing capacity in the greenhouse. The software running on the microcomputer and the microcomputer itself can be simplified in some design and function. It only needs to manage the sensors and devices in the greenhouse and complete the communication with the server. This microcomputer only needs to have the ability to process Internet protocol, has a communication port, and can meet basic needs with the signal processing function of sensors and equipment, and even no need to switch, keyboard, or display. Such a microcomputer is generally called the greenhouse slave computer.

The sensors use some communication methods to connect to the greenhouse lower computer, which collects the data transmitted by the sensors in real-time, then communicates with the server and receives the server's instructions to manage and control the greenhouse sensors and equipment.

The most commonly used lower computers for data acquisition and control operation in greenhouse systems are Microcomputer, TelosB Platform, Raspberry PI and Arduino, and Android industrial tablet. They have advantages such as low cost, strong expansibility, customizable function, and strong compatibility[13].

3.2.1.1. Microcomputer

Microcomputer (MCU)'s functions include A/D conversion, data storage, and controlling the wireless transceiver chip's working state. It also includes online simulation, a programming interface, and convenient online debugging, which provides convenience for an intelligent greenhouse to use base station debugging[69].

Because of its excellent cost performance and high integration, low power consumption, small size, high reliability, and robust control ability, MCU is favored by various greenhouse monitoring systems. Park et al. used a single-chip microcomputer as the next computer in their greenhouse monitoring system[64,70–72]. Wang et al. used a single-chip microcomputer with mighty processing power and rich internal peripheral ports, ultra-low power consumption is its most significant feature and has five power-saving modes. The disadvantage is the battery power supply, so the energy is limited [9]. Lara et al. selected and used a low-cost and low-power MCU ESP32, which has highly integrated characteristics that enable powerful function and processing with few peripheral devices, to acquire sensor data in the greenhouse after comparison [112]. Gutierrez et al. utilized ESP8266 and took into account for its processing capacity in greenhouses [113].

3.2.1.2. Arduino

Arduino, by contrast, is an open-source electronics platform[61]. Essential features of Arduino are Universal Asynchronous Receiver/Transmitter (UART) communication, analog to digital converter, and General Purpose Input Output (GPIO) pin. Atmega328p chip is very cheap to replace, compared with other microcontrollers; its performance-price ratio is also satisfactory[73]. Arduino's mega board provides multiple input analog and I/O digital, making it easy to obtain environmental factor parameters by reading sensor data[74]. Arduino can sense the surrounding environment by receiving input signals from various sensors and influencing the surrounding environment by controlling actuators such as heaters and water pumps[75]. Mehra et al. used Arduino to activate the corresponding control system[76]. Rodriguez et al. used Arduino as the central node to send data to a central big data repository and monitor and forecast client applications[77]. Groener et al. used Arduino to support the manual operation of the controller[78]. The Arduino board also reads the status of the actuator and transmits it to the remote monitoring station. Gutierrez et al. utilized ESP8266 combined with Arduino, where the Arduino deal data from various sensors and transmits them to the ESP8266 for the next communication, to provide the support for data communication system [114]. The results show that the system achieves effective and real-time monitoring of the greenhouse.

3.2.1.3. TelosB Platform

TelosB Platform is a kind of microprocessor widely used in the early stage. It uses an IEE802.15.4 RF transceiver and has a transmission rate of 250kbps. It is an open-source, low-power platform perfectly compatible with the TinyOS operating system and can be used to obtain data and program through a Universal Serial BUS(USB) interface[79]. Because it consumes less current, it has a better life. However, the TelosB

Platform is not widely used because of its small population[80].

3.2.1.4. Raspberry Pi

Raspberry Pi is a cheap, small-sized computer that could connect to a monitor. Raspberry pie is based primarily on the Linux operating system. It can handle large amounts of data, work better in cumbersome processes, and be very inexpensive with almost the same functionality as a computer[60]. In a greenhouse, sensors support installing various sensors by connecting to a Raspberry Pi microcontroller and can act as a cloud data logger, making Raspberry Pie the ideal microcontroller for a greenhouse monitoring system[81]. Besides, with the development of Raspberry Pi, newer models have built-in WIFI and Bluetooth modules, making it easy to add projects to wireless mode. As a result, some recent papers have used the Raspberry Pi as a slave to their monitoring system. Liao et al. used raspberry Pie 2 to connect sensors to the cloud server[7,77,82,83]. Mehra et al. used Raspberry Pie 3 to fit the data into a neural network and make decisions for control[76]. Kothawade et al.used raspberry pie to write timestamps and environmental factors to Comma-Separated Values (CSV) files, save them to the server, and issue/off commands to the controller[60].

The features of these slave computers are different, but their functions and usage are the same. The difference is that programs running on the slave computers have different development languages, platforms, and costs. All platforms are used by researchers all over the world. Researchers are advised to choose the mainstream development platform of slave computers, which has a lower cost and still maintains important updates and production.

3.2.2. IoT Communication Protocol in Greenhouse

3.2.2.1 Wired Mode

In the past few decades, the greenhouse management system has been significantly developed. A variety of sensors are used to measure various environmental information. However, most typical sensor monitoring systems are developed based on a wired connection, using a serial port to achieve the internal transmission of greenhouse data

[68,84].

The serial port is a familiar industrial wired communication interface. Sensors can easily connect to devices such as microcomputers or single-chip computers by using a serial port. Serial interfaces are divided by electrical standards and protocols[68,85]. RS-232-C and RS-422 require that each pin of the connector's signal content be regulated, even the signal level be regulated, and only one-way transmission can be completed. There are problems such as common noise and interference, and the communication distance is very short. The new generation RS-485 solves the problem of communication distance[86]. It can transmit distances of tens of meters or even thousands of meters. Bus transceivers are also highly sensitive and can form distributed systems, but there are also wiring difficulties.

The wired system limits the ease of installation and expandability, increases the cost of installation and maintenance, and is prone to the aging of lines due to high humidity and light intensity in the greenhouse. Rodents may damage wires, and so on. If there are thick wires in the planting area, it may hinder planting, and improvements are needed[87].

3.2.2.2. Wireless Mode

In recent years, wireless technology has developed rapidly. It began with military and industrial control and is now widely used in environmental monitoring and agriculture[71,88].

Wireless sensor networks (WSNs) usually consist of nodes powered by batteries or power supply, equipped with specific sensors. These sensors collect the required information and transmit it to a lower computer through wireless communication. The lower computer stores or sends the received data for future processing or dynamic use for monitoring, control, and other purposes[88].

According to the definition of the IoT[89], WSNs are a solution based on the IoT[90]. WSNs are primarily suited for low bandwidth and latency tolerance and eliminate the enormous cost of wiring[64]. In addition, the wireless sensor network based on the IoT has the characteristics and advantages of good mobility, good stability, good maintainability, easy installation, and expandability according to actual needs[79,91].

Today, WSNs has become one of the most critical technologies in intelligent agricultural automation based on the IoT. In precision agriculture, WSNs can play an essential role in managing and managing irrigation water resources, understanding crop changes to assess optimal harvest points, estimating fertilizer requirements, and predicting crop performance more accurately[92].

WSNs are a component of ubiquitous computing. However, these sensors operate with power and power constraints and should give priority to meeting application needs. Designing a new wireless sensor node is a challenging task involving many different parameters needed to evaluate the target application, including range, antenna type, target technology, components, memory, storage, power, lifetime, security, computing power, communications technology, power, size, programming interfaces, and applications[88].

To achieve these goals, it has developed several IoT communication protocols. At present, the leading IoT communication protocols include LoRa, NB-IoT, ZigBee, Wi-Fi, Bluetooth, and some private protocols have been used.

A: Zigbee

ZigBee is a wireless network protocol with low speed and short distance transmission, which adopts IEEE 802.15.4 standard. The main features are low speed, low power consumption, low cost, supporting a large number of network nodes, supporting various network structures, and self-organizing. The characteristic of automatic networking is that some base stations can be used even if they are destroyed, and each node has the same status[7]. The price of ZigBee is also satisfactory. Its transmission rate can meet the requirements of image data transmission[7,64]. Its most prominent advantage is fast response speed. Generally, it only takes 15ms to switch from sleep to a working state, and it only takes 30ms for nodes to connect to the network.

ZigBee can adopt a star, sheet, and mesh network structure. In theory, the maximum number of nodes is more than 60 thousand, so ZigBee is often chosen as the communication protocol in a large, intelligent greenhouse[71].

B: LoRa

LoRa is a wireless network protocol with low power consumption and long-distance transmission. IEEE 802.15.4g standard is adopted[93]. The main features are low-speed, low-cost, supporting a large number of nodes, supporting various network structures, ad hoc network, and automatic repair function. The most crucial feature of LoRa is its extreme endurance[94]. If LoRa equips with two double-A batteries, the equipment will operate continuously for up to 10 years in theory. The transmission distance is relatively long, and it supports the star topology structure. Some researchers have established LoRa P2P communication between gateway (Master), sensor hub (Slave), and controller (Slave)[95]. The theoretical maximum number of nodes in a LoRa network is more than 60 thousand. The response speed of LoRa is fast. Generally, it only takes tens of MS to switch from sleep to a working state, and it only takes 1 s for nodes to connect to the network. However, LoRa is a relatively new technology, so its users are not as many as ZigBee. It is necessary to consider in LoRa communication for agriculture, including the capture of data from nodes in motion such as vehicles, without the need for fixed gateways [115].

C: NB-IoT

The NB-IoT is based on a cellular network. NB-IoT is a low-power Wan like LoRa. It is a wireless network protocol with low power consumption and long-distance transmission. The main features are low speed, low power consumption, low cost, long-distance, supporting a large number of network nodes, and supporting various network structures[96]. The transmission range is slightly lower than that of LoRa, but the transmission speed is improved. The cost, endurance, and the number of theoretical nodes are close to LoRa. The disadvantage of NB-IoT lies in the response speed and the telecom operators. The response speed of NB-IoT is slow. Generally, it takes 3S to switch from sleep to a working state, and it takes 3S for nodes to connect to the network. Moreover, it must work and upgrade based on the Telecom operator's base station, so it is challenging to build NB-IoT in remote areas. In contrast, LoRa has a lower cost, long-distance, and lower power consumption than NB-IoT. Moreover, there is no need to use the base station of the mobile operator.

D: Wi-Fi

As the critical access method of Wireless Local Area Network (WLAN), the Wi-Fi network has become the synonym of WLAN[97]. Wi-Fi has the highest transmission rate among many wireless connections so that it can support real-time video transmission. However, other connection methods are generally low in speed and challenging to meet real-time video transmission requirements. Simultaneously, Wi-Fi has the shortest working transmission delay, which can support the real-time control of ultra-short delay devices.

However, Wi-Fi equipment's power consumption is high, the transmission distance is also short, and the network capacity is low. A single central base station only supports 16-64 devices to connect at the same time. Therefore, it is suitable for data transmission with a small scale, short distance, high transmission rate, and high response rate[61,78]. Most greenhouses that use Wi-Fi as wireless transmission and communication protocol have a relatively small scale[73,79]. When Wi-Fi is used as a data transmission mode, an independent power supply should be used as far as possible to ensure endurance time.

E: Bluetooth

Bluetooth is a small range, short-range wireless communication technology, has a history of 20 years, and has developed many versions. Bluetooth has a short transmission distance, high power consumption, and a cumbersome connection process. Some early papers on the IoT in the greenhouse used Bluetooth communication protocol[42]. However, because IEEE 802.15.1 standard is no longer maintained, its various versions are incompatible and inconvenient to use, resulting in weak networking ability, not suitable for multi-point control, almost unable to meet the networking of large-scale greenhouse. At present, Bluetooth has been almost eliminated.

F: Private Protocols

Klaring et al. used sophisticated wireless sensor devices to build the network, but these were expensive and private[42]. Liu et al. used Crossbow's products to build a wireless sensor network, which costs $400 for a central greenhouse node[5]. Inc sensicast uses sense cast systems to establish a private sensor network in a small space[18]. Commercial companies' greenhouse environmental control systems such as climate control systems, priva, Vaisala, and autogrow are private and inflexible.

All of the research above uses private protocols. Although some sensors are very advanced and sophisticated, their scalability and cost are not acceptable. More researchers prefer to use other non-private protocols.

With the development of wireless technology and various problems caused by a wired connection, most papers have not used a wired connection in recent years. Most of the latest wireless connection methods have the following advantages: most are very flexible and convenient, often only need a simple device like a router to set up; a large number of physical connection lines are omitted, and the cost is reduced accordingly; a wide variety of wireless network structures can be achieved without complex wiring; some also support self-contained networks, network expansion often only involves the expansion of a single node, the scalability is robust; the transmission speed has also been greatly improved; besides, stability and anti-interference capabilities have been greatly improved; and often wireless network devices are small and easy to move. Besides, the stability and anti-interference ability have also been greatly improved; and most wireless network equipment is small and easy to move.

G：Summary and Comparison

As can be seen from Table C.1, at present, ZigBee communication protocol is used in most papers, and Bluetooth is almost eliminated. However, Lora and NB-IoT still have a lot of room to grow, and Wi-Fi was and still is a certain market. The reason can be seen in Table B.1. In its early days, ZigBee already supported 60,000 network nodes and reached a top speed of 250 Kbps, twice the speed of Lora, a later technology, and two years of standby time could meet the needs of most people, so in the early days, ZigBee is arguably the most cost-effective choice. Although Bluetooth has a higher transmission rate, but the battery life is short, and the fatal disadvantage of Bluetooth is that the single network capacity is too small, cannot adapt to the multi-parameter multi-position sensor system in the greenhouse. Hence, the elimination of Bluetooth is inevitable. With the expansion of commercial greenhouse areas and the improvement of people's requirements on endurance, LoRa and NB-IoT appeared. They have wide coverage characteristics, low power consumption, powerful management platform, and rich terminal types. Although the two communication protocols' power consumption is low, unlike NB-IoT, LoRa's power consumption is better than that of NB-IoT due to the different wake-up methods. NB-IoT cannot be self-organized and must rely on the operator's work. However, LoRa uses an open frequency band to be ad hoc or rely on the operator's network. - In terms of security and anti-interference capability, NB-IoT can work in an automatic network. At the same time, the cost of NB-IoT will be higher than LoRa. Wi-Fi technology is relatively mature, but the power consumption is larger than the above several communication protocols.

According to the above comparison, if the monitoring parameters are complex, the number of sensors is large, and there is no longer a long transmission distance, ZigBee is a better fit than others; Lora and NB-IoT are good choices when monitoring data is not only complex but also transmitted over long distances. For data like the video that requires high speed and low latency, adding Wi-Fi technology is a good choice. Multiple technologies can also be used. For example, Zhang et al. proposed a combination algorithm of NB-IoT and LoRa[72]. The communication mode of one master node and multiple sub-nodes is adopted to meet the large-scale monitoring needs. Among them, NB-IoT is used in the design of the master node, and LoRa communication technology, sensor technology, and photoelectric conversion technology are used in the design of the sub-node. This method's advantage is that NB-

IoT and LoRa's combination increases the transmission distance and reduces the Wan information monitoring system's operation cost.

3.2.3. Communicate Protocol Between Greenhouse and Server

Wired USB is an external bus standard with plug-and-play characteristics, flexible connection, fast transmission speed, and independent power supply. It can be used to connect the slave computer and the server. There is no loss of bandwidth when connecting 127 external devices. However, due to the wired connection, the cost is high, the wiring is inconvenient, and the transmission distance is limited.

At present, Ethernet is widely used to communicate between the slave computer and the greenhouse monitoring system server. There are two ways of direct transmission and router forwarding. In the past, Ethernet was usually used to connect directly to the slave computer for communication. The slave computer collected sensor data directly connected to the Internet using wired Ethernet and transmitted it to the server. This structure is simple, and the cost is low, but it has a considerable limitation in the wiring, so the slave computer must directly connect to the Ethernet port.

Moreover, most greenhouses are located in remote places, so it is difficult to install a wired Ethernet network to use a mobile operator network to complete communication[98]. Due to the simple structure, weak performance, and function of the slave computer, it is generally unable to use additional communication connection for backup. Therefore, in the case of Ethernet failure, it is impossible to switch to another standby communication mode to maintain the greenhouse monitoring system's continuous operation.

Therefore, it is necessary to introduce a wireless communication mode to expand and enhance the communication between the slave computer and the server. Generally speaking, the more reasonable way is to add a more powerful router. Many equipment manufacturers have completed these devices.

General Packet Radio Service (GPRS) module is the most common way to communicate with the server[55,65,75]. The wireless remote greenhouse environment monitoring system based on Global System for Mobile communications (GSM) can send control information by SMS[9,98]. The use of digital signal process (DSP) and 3G is also one of the early popular[70]. Considering the update cost, the mixed-use of GPRS and wired Ethernet is also the right choice[97].

Some routers can connect to the Internet through a mobile communication network and wired Ethernet simultaneously and then send the data to the server through the Internet to complete remote data transmission. The mobile communication network and wired Ethernet used by the router are back up to each other, ensuring that even if one of the wired Ethernet and mobile communication networks fails, the data transmission inside and outside the greenhouse can still be completed.

3.3. Server Information Processing Subsystem

The development direction in modern agricultural production management is more intelligent and automated, reducing farmers' workload, providing intelligent decision-making, and improving the greenhouse environment's stability. In the greenhouse monitoring system based on the IoT, researchers have made more efforts to do this. In the early, server-side functions were relatively simple and could only obtain greenhouse data remotely[98]. Now, most of them use a B/S-based Web interface or C/S-based mobile APP-side to achieve almost all functions, allowing managers to access greenhouse environment data remotely at any time. The system has data collection, data storage, visualization, scientific analysis, alarm, and precise control of greenhouse equipment[72,99]. Regardless of the architecture used, privilege management is essential, especially hierarchical privilege management, ensuring data security[73,100].

Visualization is an essential part of data analysis. This technology can show the curve of data change[65,82,97]. For managers, the indicators of greenhouse data are understood, the overall distribution and statistical information of greenhouse data are explored intuitively, and the rules behind the data are found (e.g., more scientific planting methods). With visualization technology, Katsoulas et al. showed the change curve of monitoring data and found significant spatial variability of temperature and humidity, which proved that uneven climate in the greenhouse could affect plant growth[80]. Ferentinos developed a greenhouse climate monitoring system. They combined the greenhouse information collected by sensors with plant information and designed some comprehensive information indicators (e.g., performance indicators and plant stress index), which reduced the complexity and difficulty of greenhouse management and made planting more scientific[79]. The orchid monitoring system developed by Azaza et al. can analyze temperature and humidity factors combined with images. [12]. The temperature and humidity range with the fastest-growing leaf area of Phalaenopsis were obtained. It proves that the leaf area could be used as a measure of Phalaenopsis growth and provides a new way to analyze plants' growth status in other greenhouses[12].

With the development of network communication and storage devices, video monitoring is also added to the monitoring system. This not only helps timely and remote detection of pests and diseases but also assists the control module. [94] Yang et al. has designed a camera system for image transmission to observe plants' growth through the software without spending many human resources for field observation. People can discover problems such as pests and diseases in time and then decide whether to add fertilizers or spray pesticides.

When any failure occurs, the monitoring system can use short messages or direct alerts to notify managers[60,101]. Managers often want to eliminate dangers after alarm triggers. So recent papers have included automatic corrective measures in the monitoring system. They usually store a large number of databases for different crop growth in the system beforehand. By choosing to switch between different plants, they get some expert advice and control greenhouse factors[94]. Users can control the greenhouse equipment according to the advice[61]. The system usually provides an optimal value or interval for environmental factors. Depending on the difference between the sensor's data values and the recommended parameters, the coordinating station can take some corrective measures, such as switching on and off the electrical relay in the greenhouse to activate some activities (e.g., heating, lighting, and ventilation)[75,96,102,103].

More machine learning methods have been added to the server sub-module to help control and have achieved good results in recent years. The system triggers events based on the environmental factors it monitors. There are two types of events: warning notifications and control events. Warning events help users understand the greenhouse environment in advance, and controlling events helps to achieve automatic control[95]. The prediction algorithms include linear regression, SVM algorithm and have achieved high accuracy[77]. Others use the deep neural networks, such as the Back Propagation (BP) network[76,90], Artificial Neural Network(ANN) algorithm[70], Bayesian network[81].

In general, the server data processing function of the greenhouse monitoring platform is continuously improving. It has completed the real-time display and storage function of greenhouse data. It partly uses data visualization technology to show the changing trend of environmental parameters so that farmers can understand the general information and changing trend of the greenhouse. Some systems will provide the optimal value of each greenhouse environment parameter based on agricultural knowledge and expert recommendations and provide suggestions and a basis for farmers' decision-making. Simultaneously, many studies will combine the monitored information with control strategies such as on-off to automatically control the greenhouse environment.

With the development of machine learning and other technologies in recent years, many scholars have begun to use machine learning algorithms to analyze greenhouse images, predict the trend of future greenhouse environment changes, and have achieved good results.

4. Discussion

Through the analysis of greenhouse monitoring systems in recent 20 years, it is found that the intelligent monitoring system plays a crucial role in energy saving, emission reduction, yield increase, and quality improvement of a greenhouse. Specifically, the intelligent monitoring system can:

(1) Improve the intelligent greenhouse building system.

(2) Real-time remote monitoring of greenhouse environment to reduce human resources.

(3) Manage the greenhouse equipment system to achieve high efficiency.

(4) Alarm and take corresponding measures when the environmental parameters exceed the acceptable range.

(5) According to the needs, coordinate the greenhouse composite energy system's operation, including heating, ventilation, and lighting systems.

(6) Build an Intelligent and accurate decision-making system to reduce greenhouse energy consumption and improve environmental benefits.

(7) The reduction in energy consumption, e.g. electricity, in the greenhouse could be obviously obtained up to approximately 22% [12, 74] after using intelligent monitoring and control system.

However, after analysis, we also found that the existing monitoring system still has the following limitations, challenges, and research gaps:

(1) Most of the greenhouse environmental factors monitored in these papers are too single. Most of them only include light, environmental temperature, and humidity, as can be seen from Table B.1.

(2) Most of the literature paper only introduce the environmental factor sensors they use, and the research on the necessity of environmental factors are research gaps.

(3) The server data processing in the monitoring system developed in the early era is simple. For the selected papers in recent years, about 19% of the papers have done visual interface, but most of them are very simple, single-function, and are hard-to-use to farmers.

(4) Although 10% of the papers try to use machine learning in the greenhouse

monitoring system and have achieved good results, almost none of the papers went into production. The amount of monitoring data in most papers is too small, and the utilization rate of monitoring data is low.

(5) No monitoring system can completely achieve every module in this paper. The full implementation of all the advanced modules mentioned in this article is a significant challenge.

(6) The data's quality directly limits the accuracy of the server subsystem's control instructions. It can be said that the quality of the monitoring data limits the final effect of the whole system.

(7) It can be seen from Table A.1 that the various features of the IoT communication protocol are mutually limited. Increasing the distance and lowering power consumption will reduce the bandwidth. When high bandwidth video monitoring is needed, a high power consumption communication protocol may be used.

The three subsystems are independent of each other but influence each other. The data type and quality of the environment perception subsystem directly affect the transmission quality of the data transmission subsystem and the server information processing subsystem's visualization quality and decision-making accuracy. On the other hand, the technology adopted by the data transmission subsystem must fully consider the complexity of the parameters in the greenhouse perception subsystem and the processing convenience of the server information processing subsystem. Finally, the server information processing subsystem can often get some interesting conclusions through the algorithm to support the study of environmental parameters. The cost and quality of data transmission also need to be considered as to which technology the server information processing subsystem interacts with the user.

The goal of greenhouse system based on the IoT is to accurately collect and analyze greenhouse environment factors, regulate and control the environment of crop growth, provide intelligent and effective information services and decision-making assistance for managers, realize remote, efficient, refined, and automated agricultural production, and promote the transformation of agricultural production management from extensive to precision agriculture. In the future, to achieve this goal, we make the following suggestions:

(1) It should be considered which monitoring parameters before selecting the suitable sensors.

(2) Increase the type of parameters to monitor, such as leaf temperature and leaf humidity.

(3) Use dual backups or other solutions to cope with unexpected situations, such as power outages or other human-caused data loss.

(4) Ensure the data's accuracy and timeliness, and set up a database for easy use.

(5) Designers or engineers of monitoring systems need to consider how to make full use of data to realize accurate and timely intelligent control and early warning after obtaining complete and correct data, and how to achieve best results.

In addition, application of communication technology in greenhouse monitoring system has been summarized based on reviewed literature in this work and illustrated in Fig. 3. ZigBee is currently the mainstream among the data communication protocols within the greenhouse. USB was mainly used in the past to achieve short-distance data transmission in and out of greenhouses.

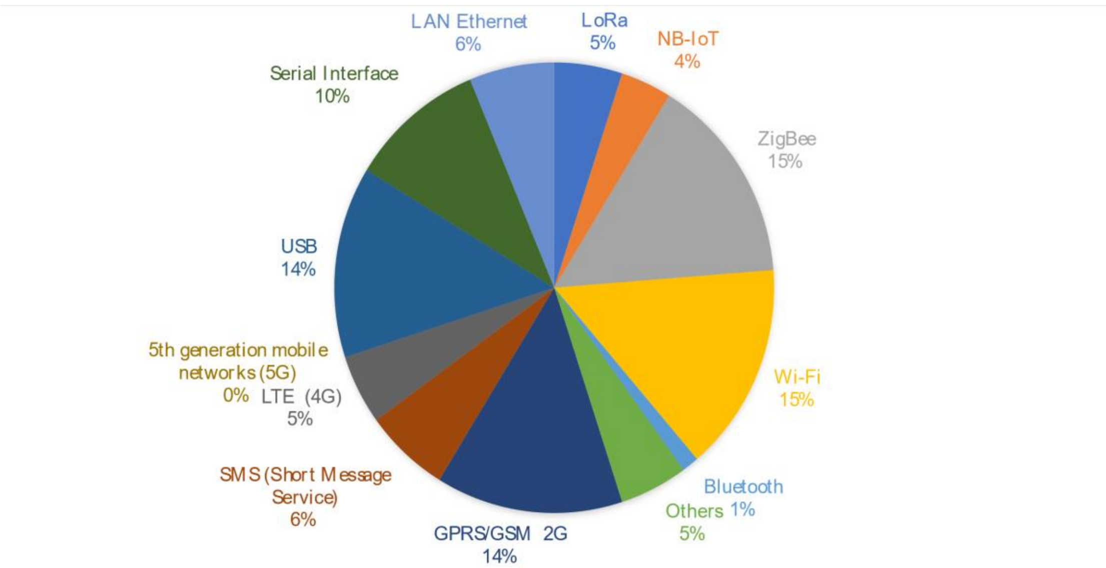


Fig 3. Application of communication technology in greenhouse monitoring system

5. Conclusion

The greenhouse equipped with an intelligent monitoring system can better maintain the greenhouse environment's stability and manage greenhouse crops in a more timely and accurate manner. In this situation, resource utilization efficiency is improved, and greenhouse buildings' energy consumption is reduced. Therefore, this paper reviews the literature on the existing agricultural greenhouse monitoring system. The ultimate goal of this work is to build a bridge between the knowledge of biology and the Internet of Things and intelligent systems to facilitate research on greenhouse monitoring systems. This article provides agricultural experts with technical knowledge on the Internet of Things and intelligent systems; At the same time, the in-depth study of environmental parameters provides effective reference information for technical engineers to ensure that the data transmitted in the Internet of Things and the data processed and used by the server are effective and high quality. The establishment of a set of standards for greenhouse monitoring systems will accelerate the contribution in this field and enable greenhouse monitoring systems to move from experimental to practical production.

Meanwhile, design specifications and technical trends of the greenhouse monitoring system are extracted. The main valuable and concise conclusions are as follows: Monitoring of plant parameters is necessary in addition to general environmental parameters. The development and application of the slave computer have been mature, a wide variety and excellent functions; the price is generally low. There are various kinds of communication protocols in the IoT in the greenhouse. The bandwidth, length, and battery life are restricted by each other, which can be compared and selected according to different needs. The communication protocol between the lower computer and the server has gradually changed from the wired mode to the wireless mode. The application of machine learning in the greenhouse monitoring system is still relatively small, but it will become a future trend.

ZigBee is currently the mainstream among the data communication protocols within the greenhouse. New technologies such as LoRa and NB-IoT will be more developed and applied. The advanced mobile communication technology represented by 4G will become the inevitable data communication trend inside and outside the greenhouse. According to the proportion of various communication protocols used in the papers in recent years, WI-FI can be used in the greenhouse, also can be used between the greenhouse and the server, so WI-FI accounts for a large proportion, but because of the inherent disadvantage of high power consumption in the application has certain limitations, and not all data transmission requirements and WIFI the same speed.

6. Future suggestion

In the future, with the popularity of the 5G technology, the greenhouse monitoring system using the 5G of data transfer module is a valuable research topic, which will lead to faster data transmission in the environment. Besides, with the development of a large amount of data, greenhouse monitoring will be better combined with artificial intelligence and machine learning, further refine unmanned greenhouse management, and further improve greenhouse construction's energy utilization.

Acknowledgments

This research was financially supported by the National Key Research and Development Program of China: Sino-Malta Fund 2019: “Research and Demonstration of Real-time Accurate Monitoring System for Early-stage Fish in Recirculating Aquaculture System” (AquaDetector, Grant No. 2019YFE0103700), Overseas High-level Youth Talents Program (China Agricultural University, China, Grant No. 62339001), China Agricultural University Excellent Talents Plan (Grant No. 31051015), Major Science and Technology Innovation Fund 2019 of Shandong Province (Grant No. 2019JZZY010703), National Innovation Center for Digital Fishery, and Beijing Engineering and Technology Research Center for Internet of Things in Agriculture. The authors also appreciate constructive and valuable comments provided by reviewers.

Nomenclature

Abbreviations

ANN: Artificial Neural Network

BP: Back Propagation

CO_2: carbon dioxide

CSV: Comma-Separated Values

DSP: digital signal process

ERI: emergence rate index

GPIO: General Purpose Input Output

GPRS: General Packet Radio Service

GSM: Global System for mobile communications

IPCC: Intergovernmental Panel on Climate Change

IoT: Internet of Things

MCU: Microcomputer

PWS: plant water stress

SVM: Support Vector Machine

UART: Universal Asynchronous Receiver/Transmitter

USB: Universal Serial BUS

VPD: Vapour Pressure Deficits

WSNs: Wireless sensor networks

WLAN: Wireless Local Area Network

Appendix A

Table A.1
Comparison of severe IoT communication protocols study and the corresponding investigation results.

Technique Type	LoRa	NB-IoT	ZigBee	Wi-Fi	Bluetooth	GPRS/GSM 2G	LTE	5th generation mobile networks
Technical Criterion	802.15.4g	NB-IoT	802.15.4	802.11n/ac	802.15.1	1xRTT/CDMA	LTE-TDD And LTE-FDD	5G NR
Working Current	10mA	40mA	10mA	50mA	10mA	400mA	900mA	
Maximum Endurance / With AA battery	10 Years	10 Years	2 Years	Within One Day	Within One Month	Within One Week	Within One Week	Within One Week
Maximum Transmission Distance	20km	15km	100m	100m	100m-300m	Over 1km	Over 1km	Over 1km
Peak Information Rate	50kbps	100kbps-250kbps	250 kbps	6.9Gbps - 10Gbps	1Mbps-2Mbps	128 kbps	100Mbps	1 Gbps
Single network capacity	Over 60000	Over 60000	60000	16-64	8	1	1	1

Working transmission delay	Adjustable, generally less than 100ms	6s	About 300ms	20ms -30ms	50ms	Over 100ms	50ms	1ms
Time to establish a new connection	1s	3s	30ms	3s	3-10s	Need To Say Cnnected	Need To Say Cnnected	Need To Say Cnnected
Whether Need Mobile Communications Support	Need Mobile Communications Support/ Need A Private Network	Need Mobile Communications Support	Need Build A private network	Need Build A private network	Need Build A Private Network	Mobile Communications Support (Has been phased out)	Mobile Communications Support	Mobile Communications Support
Chip Cost	2 Dollars	5 Dollars	2 Dollars	5-10 Dollars	2-3 Dollars	Discontinued	Over 20 Dollars	Over 100 Dollars

Appendix B

Table B.1

Study results of sensor used in greenhouse

Publication/ reference	Greenhouse model	Crops		Year	Supported by project	Greenhouse implements	Sensors for environment				Sensors for crops		Sensors for the land		Others
		Included	Type				T	H	L	CO_2	T	H	H	T	
[64]	Soil cultivation	√	Tomato	2009	√	Korea	√	√			√	√			
[74]	Soil cultivation	√	Cantonese	2016	√	Thailand	√	√					√		
[75]	Soil cultivation			2017		India	√	√	√				√		
[104]	Hydroponics	√	Cherry, Salmon Rose, Orange	2013		Brazil			√						
[83]	Hydroponics			2016		Thailand	√	√	√						
[76]	Hydroponics	√	Tomato	2018		India		√	√						
[97]				2018	√	China	√	√	√						
[61]				2017		India	√						√		

Publication/ reference	Greenhouse model	Crops		Year	Supported by project	Greenhouse implements	Sensors for environment				Sensors for crops		Sensors for the land		Others
		Included	Type				T	H	L	CO_2	T	H	H	T	
[80]				2017	√	Greece	√	√	√						
[79]	Hydroponic	√	Tomato	2015	√	Greece	√	√			√				
[5]				2007	√	China	√		√				√		
[11]	Soil cultivation	√	Tomato	2014	√	Croatia	√	√					√	√	
[77]	Soil cultivation	√	Rose	2017		Portugal	√	√	√				√		
[10]	Soil cultivation	√	Tomato	2017		Pakistan	√	√	√						
[12]	N		N	2016		Sweden		√	√	√					
[55]	N		N	2017		Tunisia							√		
[7]	Soil cultivation	√	Phalaenopsis	2017	√	Taiwan, China	√	√	√	√					
[70]	N		N	2012	√	China				√					
[73]	N		N	2019		Vietnam	√	√	√	√					
[42]	N		N	2007	√	Israel	√		√	√					

Publication/ reference	**Greenhouse model**	**Crops**		**Year**	**Supported by project**	**Greenhouse implements**	**Sensors for environment**				**Sensors for crops**		**Sensors for the land**		**Others**
		Included	**Type**				T	H	L	CO_2	T	H	H	T	
[65]	Soil cultivation	√	N	2011	√	Korea	√	√			√				
[105]	Soil cultivation	√	Vegetable	2010	√	China	√	√					√		
[18]	Soil cultivation	√	Tomato	2006		Italy	√	√						√	
[98]	N		N	2012		China	√	√							
[9]	N		N	2008	√	China	√	√	√						
[78]	Soil cultivation	√	Tomato	2015	√	Kenya	√	√					√		
[106]	N		N	2009		Spain	√	√							
[71]		√		2007	N	China	√	√	√						
[82]	Hydroponic	√	Barley	2018	√	Morocco	√	√	√	√			√		
[102]				2018	√	New Zealand	√	√	√	√			√		
[98]				2012	√	China	√	√							
[100]				2017	√	China	√	√	√	√			√		

Publication/ reference	Greenhouse model	Crops		Year	Supported by project	Greenhouse implements	Sensors for environment				Sensors for crops		Sensors for the land		Others
		Included	Type				T	H	L	CO_2	T	H	H	T	
[99]				2011	√	China	√	√	√	√			√		
[93]				2018		Viet Nam	√	√	√	√			√		
[94]	Soil cultivation	√	Dragon *fruit*	2020		China	√	√	√	√			√		
[95]	Soil cultivation	√	Organic Vegetables	2019	√	China	√	√	√	√			√		
[96]				2019	√	China	√	√	√						
[72]				2018	√	China	√	√		√			√		
[81]	Hydroponics			2017	√	Malayan	√	√	√				√		pH/WC/WT
[107]	Hydroponics	√	Lettuce	1999	√	Portugal	√	√							pH/WC/WOC
[101]	Hydroponics			2017	√	Indonesia	√	√	√	√					

Note:

T: Temperature
H: Humidity

L: Light
WC: Water Conductivity
WT: Water Temperature
WOC: Water Oxygen Concentration

Appendix C

Table C.1
Research results of communication protocol in greenhouse and between greenhouse and server

Publication/reference	IoT						Mobile communication technology				Wired connection		
	LoRa	NB-IoT	ZigBee	Wi-Fi	Bluetooth	Others	GPRS/ GSM 2G	SMS (Short Message Service)	LTE (4G)	5th generation mobile networks (5G)	USB	Serial Interface	LAN Ethernet
[76]											√	√	
[64]			√						√				√
[97]				√			√					√	√
[75]							√				√		
[61]				√					√		√	√	
[80]				√							√		
[79]				√							√		

Publication/reference	IoT						Mobile communication technology				Wired connection		
	LoRa	NB-IoT	ZigBee	Wi-Fi	Bluetooth	Others	GPRS/GSM 2G	SMS (Short Message Service)	LTE (4G)	5th generation mobile networks (5G)	USB	Serial Interface	LAN Ethernet
[5]						Private MICAz	√	√					
[11]				√		private SunSPOT	√				√		
[77]			√						√				√
[10]				√							√	√	√
[12]			√				√						
[55]			√				√						
[7]			√	√									
[70]									3G			√	
[73]				√							√	√	
[42]						Private protocol							

Publication/reference	IoT						Mobile communication technology				Wired connection		
	LoRa	NB-IoT	ZigBee	Wi-Fi	Bluetooth	Others	GPRS/GSM 2G	SMS (Short Message Service)	LTE (4G)	5th generation mobile networks (5G)	USB	Serial Interface	LAN Ethernet
						s							
[65]			√								√		
[105]			√				√	√					
[18]						Private							√
[98]							√	√				√	
[9]				√								√	
[78]				√			√	√					
[106]			√				√						
[71]			√										
[82]				√	√								
[102]			√			nRF905					√		
[98]							√	√					
[100]			√										

Publication/reference	IoT						Mobile communication technology				Wired connection		
	LoRa	NB-IoT	ZigBee	Wi-Fi	Bluetooth	Others	GPRS/GSM 2G	SMS (Short Message Service)	LTE (4G)	5th generation mobile networks (5G)	USB	Serial Interface	LAN Ethernet
[99]						nRF905							
[93]	√		√										
[94]	√												
[95]	√												
[96]		√											
[72]	√	√											
[101]		√		√									
[69]						nRF905			√		√		

References

[1] FAO, Climate change, agriculture and food security. Food and Agirculture Organization of the United Nations, Roman., FAO Rome, 2016.

[2] S.C. University of California, Solar Greenhouses Generate Electricity and Grow Crops at the Same Time, University Relations, University of California Santa Cruz, 2016.

[3] E. Iddio, L. Wang, Y. Thomas, G. McMorrow, A. Denzer, Energy efficient operation and modeling for greenhouses: A literature review, Renewable and Sustainable Energy Reviews. 117 (2020) 109480.

[4] Y. Guo, H. Zhao, S. Zhang, Y. Wang, D. Chow, Modeling and Optimization of Environment in Agricultural Greenhouses for Improving Cleaner and Sustainable Crop Production, Journal of Cleaner Production. (2020) 124843.

[5] H. Liu, Z. Meng, S. Cui, A Wireless Sensor Network Prototype for Environmental Monitoring in Greenhouses, in: 2007 International Conference on Wireless Communications, Networking and Mobile Computing, IEEE, Shanghai, China, 2007: pp. 2344–2347. https://doi.org/10.1109/WICOM.2007.584.

[6] L. Gonda, C.E. Cugnasca, A proposal of greenhouse control using wireless sensor networks, in: Computers in Agriculture and Natural Resources, 23-25 July 2006, Orlando Florida, American Society of Agricultural and Biological Engineers, 2006: p. 229.

[7] M.-S. Liao, S.-F. Chen, C.-Y. Chou, H.-Y. Chen, S.-H. Yeh, Y.-C. Chang, J.-A. Jiang, On precisely relating the growth of Phalaenopsis leaves to greenhouse environmental factors by using an IoT-based monitoring system, Computers and Electronics in Agriculture. 136 (2017) 125–139. https://doi.org/10.1016/j.compag.2017.03.003.

[8] N. Xu, A survey of sensor network applications, IEEE Communications Magazine. 40 (2002) 102–114.

[9] C. Wang, C. Zhao, X. Qiao, X. Zhang, Y. Zhang, The Design of Wireless Sensor Networks Node for Measuring the Greenhouse's Environment Parameters, in: D. Li (Ed.), Computer And Computing Technologies In Agriculture, Volume II, Springer US, Boston, MA, 2008: pp. 1037–1046. https://doi.org/10.1007/978-0-387-77253-0_36.

[10] M.F. Siddiqui, A. ur Rehman Khan, N. Kanwal, H. Mehdi, A. Noor, M.A. Khan, Automation and monitoring of greenhouse, in: 2017 International Conference on Information and Communication Technologies (ICICT), IEEE, Karachi, 2017: pp. 197–201. https://doi.org/10.1109/ICICT.2017.8320190.

[11] G. Martinović, J. Simon, Greenhouse microclimatic environment controlled by a mobile measuring station, NJAS - Wageningen Journal of Life Sciences. 70–71 (2014) 61–70. https://doi.org/10.1016/j.njas.2014.05.007.

[12] M. Azaza, C. Tanougast, E. Fabrizio, A. Mami, Smart greenhouse fuzzy logic

based control system enhanced with wireless data monitoring, ISA Transactions. 61 (2016) 297–307. https://doi.org/10.1016/j.isatra.2015.12.006.

[13] S. Mann, I. Harris, J. Harris, The development of urban renewable energy at the existential technology research center (ETRC) in Toronto, Canada, Renewable and Sustainable Energy Reviews. 10 (2006) 576–589.

[14] A.R. Yanes, P. Martinez, R. Ahmad, Towards automated aquaponics: A review on monitoring, IoT, and smart systems, Journal of Cleaner Production. (2020) 121571.

[15] A. Awasthi, S.R.N. Reddy, Monitoring for precision agriculture using wireless sensor network-a review, Global Journal of Computer Science and Technology. (2013).

[16] A. Tzounis, N. Katsoulas, T. Bartzanas, C. Kittas, Internet of Things in agriculture, recent advances and future challenges, Biosystems Engineering. 164 (2017) 31–48. https://doi.org/10.1016/j.biosystemseng.2017.09.007.

[17] F. Fourati, M. Chtourou, A greenhouse control with feed-forward and recurrent neural networks, Simulation Modelling Practice and Theory. 15 (2007) 1016–1028.

[18] M. Mancuso, F. Bustaffa, A wireless sensors network for monitoring environmental variables in a tomato greenhouse, in: 2006 IEEE International Workshop on Factory Communication Systems, IEEE, Torino, Italy, 2006: pp. 107–110. https://doi.org/10.1109/WFCS.2006.1704135.

[19] E. Putter, J. Gouws, An automatic controller for a greenhouse using a supervisory expert system, in: Proceedings of 8th Mediterranean Electrotechnical Conference on Industrial Applications in Power Systems, Computer Science and Telecommunications (MELECON 96), IEEE, 1996: pp. 1160–1163.

[20] N. Bennis, J. Duplaix, G. Enéa, M. Haloua, H. Youlal, Greenhouse climate modelling and robust control, Computers and Electronics in Agriculture. 61 (2008) 96–107.

[21] Y. Song, X. Huang, Y. Feng, A kind of temperature and humidity adaptive predictive decoupling method in wireless greenhouse environmental test simulation system, Advance Journal of Food Science and Technology. 5 (2013) 1395–1403.

[22] J.I.L. Morison, D.W. Lawlor, Interactions between increasing CO2 concentration and temperature on plant growth, Plant, Cell & Environment. 22 (1999) 659–682.

[23] J. Goudriaan, M.H. Unsworth, Implications of increasing carbon dioxide and climate change for agricultural productivity and water resources, Impact of Carbon Dioxide, Trace Gases, and Climate Change on Global Agriculture. 53 (1990) 111–130.

[24] T.R. Wheeler, G.R. Batts, R.H. Ellis, P. Hadley, J.I.L. Morison, Growth and yield of winter wheat (Triticum aestivum) crops in response to CO 2 and temperature, The Journal of Agricultural Science. 127 (1996) 37–48.

[25] K. Popovski, Greenhouse climate factors, GHC Bulletin. (1997).

[26] G.R. Batts, J.I.L. Morison, R.H. Ellis, P. Hadley, T.R. Wheeler, Effects of CO2

and temperature on growth and yield of crops of winter wheat over four seasons, European Journal of Agronomy. 7 (1997) 43–52.
[27] Q. Xu, B. Huang, Effects of differential air and soil temperature on carbohydrate metabolism in creeping bentgrass, Crop Science. 40 (2000) 1368–1374.
[28] Y.-J. Huang, N. Evans, Z.-Q. Li, M. Eckert, A.-M. Chèvre, M. Renard, B.D. Fitt, Temperature and leaf wetness duration affect phenotypic expression of Rlm6-mediated resistance to Leptosphaeria maculans in Brassica napus, New Phytologist. 170 (2006) 129–141.
[29] X. Verge, C. De Kimpe, R. Desjardins, Agricultural production, greenhouse gas emissions and mitigation potential, Agricultural and Forest Meteorology. 142 (2007) 255–269.
[30] M.A. FORD, G.N. Thorne, Effects of atmospheric humidity on plant growth, Annals of Botany. 38 (1974) 441–452.
[31] L.M. Mortensen, Effects of air humidity on growth, flowering, keeping quality and water relations of four short-day greenhouse species, Scientia Horticulturae. 86 (2000) 299–310.
[32] H.R. Gislerød, L.M. Mortensen, A.R. Selmer-Olsen, The effect of air humidity on growth and nutrient content of some greenhouse plants, in: Symposium on Nutrition, Growing Techniques and Plant Substrates 178, 1985: pp. 181–184.
[33] R.I. Grange, D.W. Hand, A review of the effects of atmospheric humidity on the growth of horticultural crops, Journal of Horticultural Science. 62 (1987) 125–134.
[34] Y. Juan, Z.J. Yin, Y. Hailong, T. LiHua, W. RuiJuan, Mathematical study of the effects of temperature and humidity on the mycelium growth of Pleurotus eryngii, in: 2012 First International Conference on Agro-Geoinformatics (Agro-Geoinformatics), IEEE, 2012: pp. 1–5.
[35] H.M. Rawson, J.E. Begg, R.G. Woodward, The effect of atmospheric humidity on photosynthesis, transpiration and water use efficiency of leaves of several plant species, Planta. 134 (1977) 5–10.
[36] R. Holder, K.E. Cockshull, Effects of humidity on the growth and yield of glasshouse tomatoes, Journal of Horticultural Science. 65 (1990) 31–39.
[37] L.M. Mortensen, Effect of relative humidity on growth and flowering of some greenhouse plants, Scientia Horticulturae. 29 (1986) 301–307.
[38] L.M. Mortensen, T. Fjeld, Effects of air humidity, lighting period and lamp type on growth and vase life of roses, Scientia Horticulturae. 73 (1998) 229–237.
[39] E.M. Nederhoff, Effects of CO2 concentration on photosynthesis, transpiration and production of greenhouse fruit vegetable crops, Nederhoff, 1994.
[40] P. Vance, M.H. Spalding, Growth, photosynthesis, and gene expression in Chlamydomonas over a range of CO2 concentrations and CO2/O2 ratios: CO2 regulates multiple acclimation states, Canadian Journal of Botany. 83 (2005) 796–809.
[41] C. Shuangchen, Z. Zhirong, H. Chaoxing, Z. Zhibin, Y. Xu, Rules of CO_ (2)

concentration change under organic soil cultivation and effects of CO_ (2) application on tomato plants in solar greenhouse, Acta Botanica Boreali-Occidentalia Sinica. 24 (2004) 1624–1629.
[42] H.-P. Kläring, C. Hauschild, A. Heißner, B. Bar-Yosef, Model-based control of CO2 concentration in greenhouses at ambient levels increases cucumber yield, Agricultural and Forest Meteorology. 143 (2007) 208–216. https://doi.org/10.1016/j.agrformet.2006.12.002.
[43] L.F.M. Marcelis, A.G.M. Broekhuijsen, E. Meinen, E. Nijs, M.G.M. Raaphorst, Quantification of the growth response to light quantity of greenhouse grown crops, in: V International Symposium on Artificial Lighting in Horticulture 711, 2005: pp. 97–104.
[44] P. Zhong, S. Yang, R. Qiao, T. Wang, Effect of light intensity on main quality of strawberry, Southwest China Journal of Agricultural Sciences. 24 (2011) 1219–1220.
[45] M.J. Zarei, N. Kazemi, A. Marzban, Life cycle environmental impacts of cucumber and tomato production in open-field and greenhouse, Journal of the Saudi Society of Agricultural Sciences. 18 (2019) 249–255.
[46] Y. Tang, X. Ma, M. Li, Y. Wang, The effect of temperature and light on strawberry production in a solar greenhouse, Solar Energy. 195 (2020) 318–328.
[47] A. Sønsteby, K.A. Solhaug, O.M. Heide, Functional growth analysis of 'Sonata'strawberry plants grown under controlled temperature and daylength conditions, Scientia Horticulturae. 211 (2016) 26–33.
[48] L.M. Mortensen, E. Strømme, Effects of light quality on some greenhouse crops, Scientia Horticulturae. 33 (1987) 27–36.
[49] S. HIZUKURI, The effect of environment temperature of plants on the physicochemical properties of their starches, Journal of the Technological Society of Starch. 17 (1969) 73–88.
[50] Q. Xu, B. Huang, Lowering soil temperatures improves creeping bentgrass growth under heat stress, Crop Science. 41 (2001) 1878–1883.
[51] M.A. Licht, M. Al-Kaisi, Strip-tillage effect on seedbed soil temperature and other soil physical properties, Soil and Tillage Research. 80 (2005) 233–249.
[52] P.J. Stone, I.B. Sorensen, P.D. Jamieson, Effect of soil temperature on phenology, canopy development, biomass and yield of maize in a cool-temperate climate, Field Crops Research. 63 (1999) 169–178.
[53] T. Noda, T. Kobayashi, I. Suda, Effect of soil temperature on starch properties of sweet potatoes, Carbohydrate Polymers. 44 (2001) 239–246.
[54] T.W. Mew, W.C. Ho, Effect of soil temperature on resistance of tomato cultivars to bacterial wilt, Phytopathology. 67 (1977) 909–911.
[55] F. Karim, F. Karim, A. frihida, Monitoring system using web of things in precision agriculture, Procedia Computer Science. 110 (2017) 402–409. https://doi.org/10.1016/j.procs.2017.06.083.
[56] L. Yang, W. Wei, L. Chen, W. Chen, J. Wang, Response of temporal variation of

soil moisture to vegetation restoration in semi-arid Loess Plateau, China, Catena. 115 (2014) 123–133.
[57] S.B. Hornick, Factors affecting the nutritional quality of crops, Am j Alt Ag. 7 (1992) 63–68. https://doi.org/10.1017/S0889189300004471.
[58] D.J. Cooper, J.S. Sanderson, D.I. Stannard, D.P. Groeneveld, Effects of long-term water table drawdown on evapotranspiration and vegetation in an arid region phreatophyte community, Journal of Hydrology. 325 (2006) 21–34. https://doi.org/10.1016/j.jhydrol.2005.09.035.
[59] G.-L. Wu, Z. Yang, Z. Cui, Y. Liu, N.-F. Fang, Z.-H. Shi, Mixed artificial grasslands with more roots improved mine soil infiltration capacity, Journal of Hydrology. 535 (2016) 54–60.
[60] S.N. Kothawade, S.M. Furkhan, A. Raoof, K.S. Mhaske, Efficient water management for greenland using soil moisture sensor, in: 2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES), IEEE, 2016: pp. 1–4.
[61] P. Singh, S. Saikia, Arduino-based smart irrigation using water flow sensor, soil moisture sensor, temperature sensor and ESP8266 Wi-Fi module, in: 2016 IEEE Region 10 Humanitarian Technology Conference (R10-HTC), IEEE, Agra, India, 2016: pp. 1–4. https://doi.org/10.1109/R10-HTC.2016.7906792.
[62] J. Kobza, G.E. Edwards, Influences of leaf temperature on photosynthetic carbon metabolism in wheat, Plant Physiology. 83 (1987) 69–74.
[63] D.M. Gates, Transpiration and leaf temperature, Annual Review of Plant Physiology. 19 (1968) 211–238.
[64] D.-H. Park, B.-J. Kang, K.-R. Cho, C.-S. Shin, S.-E. Cho, J.-W. Park, W.-M. Yang, A Study on Greenhouse Automatic Control System Based on Wireless Sensor Network, (n.d.) 14.
[65] D.-H. Park, J.-W. Park, Wireless Sensor Network-Based Greenhouse Environment Monitoring and Automatic Control System for Dew Condensation Prevention, Sensors. 11 (2011) 3640–3651. https://doi.org/10.3390/s110403640.
[66] O. Körner, H. Challa, Process-based humidity control regime for greenhouse crops, Computers and Electronics in Agriculture. 39 (2003) 173–192.
[67] M.L. Gleason, B.A. Edmunds, Tomato diseases and disorders, Iowa State University, University Extension, 2005.
[68] D. Wobschall, H.S. Prasad, Esbus - a sensor bus based on the SPI serial interface, in: Proceedings of IEEE Sensors, IEEE, Orlando, FL, USA, 2002: pp. 1516–1519. https://doi.org/10.1109/ICSENS.2002.1037347.
[69] J. Xiao, B. Jiang, Design for wireless temperature and humidity monitoring system of the intelligent greenhouse, in: 2010 2nd International Conference on Computer Engineering and Technology, IEEE, 2010: pp. V3-59.
[70] R. Han, Y. He, F. Liu, Feasibility Study on a Portable Field Pest Classification System Design Based on DSP and 3G Wireless Communication Technology, Sensors. 12 (2012) 3118–3130. https://doi.org/10.3390/s120303118.

[71] Q. Zhang, X. Yang, Y. Zhou, L. Wang, X. Guo, A wireless solution for greenhouse monitoring and control system based on ZigBee technology, J. Zhejiang Univ. - Sci. A. 8 (2007) 1584–1587. https://doi.org/10.1631/jzus.2007.A1584.
[72] X. Zhang, M. Zhang, F. Meng, Y. Qiao, S. Xu, S. Hour, A low-power wide-area network information monitoring system by combining NB-IoT and LoRa, IEEE Internet of Things Journal. 6 (2018) 590–598.
[73] G.N. Tran, L.H. Truong, H.T. Tran, M.T. Nguyen, A Design of Sensing Data Collection Circuits for Wireless Sensor Networks Utilizing Wi-Fi Technology, 5 (2019) 6.
[74] J. Pitakphongmetha, N. Boonnam, S. Wongkoon, T. Horanont, D. Somkiadcharoen, J. Prapakornpilai, Internet of things for planting in smart farm hydroponics style, (n.d.) 5.
[75] D.O. Shirsath, P. Kamble, R. Mane, A. Kolap, R.S. More, IOT Based Smart Greenhouse Automation Using Arduino, 5 (2017) 6.
[76] M. Mehra, IoT based hydroponics system using Deep Neural Networks, Computers and Electronics in Agriculture. (2018) 14.
[77] S. Rodríguez, T. Gualotuña, C. Grilo, A System for the Monitoring and Predicting of Data in Precision Agriculture in a Rose Greenhouse Based on Wireless Sensor Networks, Procedia Computer Science. 121 (2017) 306–313. https://doi.org/10.1016/j.procs.2017.11.042.
[78] B. Groener, N. Knopp, K. Korgan, R. Perry, J. Romero, K. Smith, A. Stainback, A. Strzelczyk, J. Henriques, Preliminary Design of a Low-cost Greenhouse with Open Source Control Systems, Procedia Engineering. 107 (2015) 470–479. https://doi.org/10.1016/j.proeng.2015.06.105.
[79] K.P. Ferentinos, N. Katsoulas, A. Tzounis, C. Kittas, T. Bartzanas, A climate control methodology based on wireless sensor networks in greenhouses, Acta Hortic. (2015) 75–82. https://doi.org/10.17660/ActaHortic.2015.1107.9.
[80] K.P. Ferentinos, N. Katsoulas, A. Tzounis, T. Bartzanas, C. Kittas, Wireless sensor networks for greenhouse climate and plant condition assessment, Biosystems Engineering. 153 (2017) 70–81. https://doi.org/10.1016/j.biosystemseng.2016.11.005.
[81] M.I. Alipio, A.E.M.D. Cruz, J.D.A. Doria, R.M.S. Fruto, A smart hydroponics farming system using exact inference in Bayesian network, in: 2017 IEEE 6th Global Conference on Consumer Electronics (GCCE), IEEE, 2017: pp. 1–5.
[82] Y. Achour, N. El Mernissi, D. Zejli, Design and Implementation of Greenhouse Remote Monitor System, in: 2018 IEEE 5th International Congress on Information Science and Technology (CiSt), IEEE, Marrakech, 2018: pp. 1–6. https://doi.org/10.1109/CIST.2018.8596660.
[83] C. Peuchpanngarm, P. Srinitiworawong, W. Samerjai, T. Sunetnanta, DIY sensor-based automatic control mobile application for hydroponics, (n.d.) 4.
[84] R. Frank, Understanding Smart Sensors, Artech House, Inc., Norwood, MA. (2000).

[85] I. Maykiv, A. Stepanenko, D. Wobschall, R. Kochan, V. Kochan, A. Sachenko, Software–hardware method of serial interface controller implementation, Computer Standards & Interfaces. 34 (2012) 509–516. https://doi.org/10.1016/j.csi.2011.10.009.

[86] Y. Jing, B. Baoliang, L. Zetao, Design of Greenhouse Environment Monitoring System——Based on RS-485 BUS and Wireless Communication, Journal of Agricultural Mechanization Research. (2013) 44.

[87] G. Vox, P. Losito, F. Valente, R. Consoletti, G. Scarascia-Mugnozza, E. Schettini, C. Marzocca, F. Corsi, A wireless telecommunications network for real-time monitoring of greenhouse microclimate, Journal of Agricultural Engineering. 45 (2014) 70–79.

[88] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, Wireless sensor networks: a survey, Computer Networks. 38 (2002) 393–422.

[89] J. Gubbi, R. Buyya, S. Marusic, M. Palaniswami, Internet of Things (IoT): A vision, architectural elements, and future directions, Future Generation Computer Systems. 29 (2013) 1645–1660.

[90] J. Yuhan, J. Yiqiong, L. Ting, Z. Man, S. Sha, L. Minzan, An improved method for prediction of tomato photosynthetic rate based on WSN in greenhouse, Biol Eng. 9 (n.d.) 7.

[91] M. Wang, G. Zhang, C. Zhang, J. Zhang, C. Li, An IoT-based appliance control system for smart homes, in: 2013 Fourth International Conference on Intelligent Control and Information Processing (ICICIP), IEEE, 2013: pp. 744–747.

[92] J.A. López Riquelme, F. Soto, J. Suardíaz, P. Sánchez, A. Iborra, J.A. Vera, Wireless Sensor Networks for precision horticulture in Southern Spain, Computers and Electronics in Agriculture. 68 (2009) 25–35. https://doi.org/10.1016/j.compag.2009.04.006.

[93] D.C. Trinh, T.C. TRUVANT, T.D. Bui, Design of automatic irrigation system for greenhouse based on LoRa technology, in: 2018 International Conference on Advanced Technologies for Communications (ATC), IEEE, 2018: pp. 72–77.

[94] Y. Yang, Design and Application of Intelligent Agriculture Service System With LoRa-based on Wireless Sensor Network, in: 2020 International Conference on Computer Engineering and Application (ICCEA), IEEE, 2020: pp. 712–716.

[95] Y.-C. Chang, T.-W. Huang, N.-F. Huang, A Machine Learning Based Smart Irrigation System with LoRa P2P Networks, in: 2019 20th Asia-Pacific Network Operations and Management Symposium (APNOMS), IEEE, 2019: pp. 1–4.

[96] Y.S. Chang, Y.H. Chen, S.K. Zhou, A smart lighting system for greenhouses based on Narrowband-IoT communication, in: 2018 13th International Microsystems, Packaging, Assembly and Circuits Technology Conference (IMPACT), IEEE, 2018: pp. 275–278.

[97] M.-H. Liang, Y.-F. He, L.-J. Chen, S.-F. Du, Greenhouse Environment dynamic Monitoring system based on WIFI, IFAC-PapersOnLine. 51 (2018) 736–740. https://doi.org/10.1016/j.ifacol.2018.08.108.

[98] W. Fei-qing, L. Lin-gong, M. Xiu-shui, Q. Jun, H. Xian-tu, Development of Wireless Monitor System on Greenhouse Environment Based on GSM, in: W. Deng (Ed.), Future Control and Automation, Springer Berlin Heidelberg, Berlin, Heidelberg, 2012: pp. 371–379.

[99] Z. Wang, S. Li, Q. Hao, L. Li, G. Zhai, Research of intelligent greenhouse remote monitor system based on embedded network and wireless transmission technology, in: 2011 International Conference on Electrical and Control Engineering, IEEE, 2011: pp. 1688–1691.

[100] X. Xing, J. Song, L. Lin, M. Tian, Z. Lei, Development of intelligent information monitoring system in greenhouse based on wireless sensor network, in: 2017 4th International Conference on Information Science and Control Engineering (ICISCE), IEEE, 2017: pp. 970–974.

[101] P. Sihombing, N.A. Karina, J.T. Tarigan, M.I. Syarif, Automated hydroponics nutrition plants systems using arduino uno microcontroller based on android, in: Journal of Physics: Conference Series, IOP Publishing, 2018: p. 012014.

[102] G.S. Gupta, V.M. Quan, Multi-sensor integrated system for wireless monitoring of greenhouse environment, in: 2018 IEEE Sensors Applications Symposium (SAS), IEEE, 2018: pp. 1–6.

[103] S.I. Cosman, C.A. Bilatiu, C.S. Martis, Development of an Automated System to Monitor and Control a Greenhouse, in: 2019 15th International Conference on Engineering of Modern Electric Systems (EMES), IEEE, Oradea, Romania, 2019: pp. 1–4. https://doi.org/10.1109/EMES.2019.8795186.

[104] F. Ludwig, D.M. Fernandes, P. Mota, R.L.V. Bôas, Electrical conductivity and pH of the substrate solution in gerbera cultivars under fertigation, Hortic. Bras. 31 (2013) 5.

[105] X. Li, X. Cheng, K. Yan, P. Gong, A Monitoring System for Vegetable Greenhouses based on a Wireless Sensor Network, Sensors. 10 (2010) 8963–8980. https://doi.org/10.3390/s101008963.

[106] A. Pawlowski, J. Guzman, F. Rodríguez, M. Berenguel, J. Sánchez, S. Dormido, Simulation of Greenhouse Climate Monitoring and Control with Wireless Sensor Network and Event-Based Control, Sensors. 9 (2009) 232–252. https://doi.org/10.3390/s90100232.

[107] P.R. Furlani, L.C.P. Silveira, D. Bolonhezi, V. Faquin, Cultivo hidropônico de plantas, Instituto Agronômico Campinas, 1999.

[108] X.Z. Bai, Z.D. Wang, L. Sheng, Z. Wang, Reliable Data Fusion of Hierarchical Wireless Sensor Networks With Asynchronous, IEEE Transactions on Control Systems Technology. 27-3 (2019) 1036-1046. https://doi.org/10.1109/TCST.2018.2797920.

[109] Q. Liu, Y.Y. Zhang, J. Shen, B. Xiao, N. Linge, A WSN-based Prediction Model of Microclimate in a Greenhouse using an Extreme Learning Approach, ICACT

Trans. Adv. Commun. Technol. 4-6(2015) 730-735. https://doi.org/10.1109/ICACT.2016.7423608.

[110] J.Z. Wang, M.Z. Chen, J.S. Zhou, P.P. Li, Data Communication Mechanism for Greenhouse Environment Monitoring and Control: An Agent-based IoT System, Information Processing in Agriculture. 7-3(2020) 444-455. https://doi.org/ /10.1016/j.inpa.2019.11.002

[111] S.Y. Lee, I.B. Lee, U.H. Yeo, R.W. Kim, J.G. Kim, Optimal Sensor Placement for Monitoring and Controlling Greenhouse Internal Environments. 188(2019) 190-206. https://doi.org/10.1016/j.biosystemseng.2019.10.005

[112] J.C.D. Lara, S. Gutierrez, F. Rodriguez, Low Cost Greenhouse Monitoring System Based on Internet of Things, in: 2019 IEEE International Conference on Engineering Veracruz (ICEV), IEEE, 2019: pp.1-6, Mexico.

[113] E. Gutierrez, S. Gutierrez, J.A. Becerril, F. Rodriguez, Low Cost Prototype for Monitoring and Remote Control in Greenhouse for Homes, in: 2018 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC), IEEE, 2018: pp. 1-5, Mexico.

[114] S. Gutierrez, R. Rocha, D. Rendon, J.C. Bernabe, etc., Tracking Greenhouses Farming Based on Internet of Technology, in book: Further Advances in IoT in Biomedical and Cyber Physical Systems, 2021.

[115] S. Gutierrez, I. Martinez, J. Varona, M. Cardona, R. Espinosa, Smart Mobile LoRa Agriculture System Based on IoT, in: 2019 IEEE 39th Central America and Panama Covention, IEEE, 2019: pp. 1-6.