Chapter 11
Plant Factory IoT Management

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Abstract Plant factory, characterized by artificially controlled operation, is internationally recognized as the most advanced stage of developments in protected agriculture. Covering biological systems management, engineering management, and IoT management, plant factories can produce the planned crop products all year long, with short growth cycles and little pollution. Breakthroughs in artificial-lighting cultivation technology of plant factories have enabled crop production in non-arable lands such as skyscrapers, deserts, islands, ships, and polar regions. Therefore, the plant factory is considered a major countermeasure for the problems of this century, including population expansion, resource shortages, food security, and environmental pollution. Furthermore, it is also viewed as a way to achieve food self-sufficiency in future space engineering and space exploration. With IoT, thorough sensing and recognition, comprehensive interconnection, and deeper integration and analysis are possible, thus bringing intelligent control and decision of plant factories. In this chapter, main components and types of plant factories are illustrated, and applications of IoT systems in plant factories are outlined, so that readers may gain a comprehensive understanding of plant factory IoT.

Keywords Plant factory · IoT · Environmental control · Industrialized seedling production

11.1 Introduction

The global population is expected to reach approximately 9.7 billion by 2050 (United Nations 2019a), and 68 percent of the world's population is projected to be urban (United Nations 2019b). The problem of insufficient labor in agriculture driven by increasing urban population has become more and more prominent. Traditional crop farming, restricted by natural conditions (climate, land and water resources), features high labor intensity and low yield. Continued urbanization will

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bring new challenges to sustainability of food supply for cities. As living standards improve, the demand for fresh, clean, and safe agricultural products has increased. Research on urban agriculture, vertical farming, and plant factories has attempted to provide new perspectives for food production systems in cities (Gentry 2019; Graamans et al. 2017). Urban agriculture could ensure the supply of local fresh food. Considering the financial value of urban space, an economically viable enterprise in this regard would require extremely high productivity (Graamans et al. 2018; O'Sullivan et al. 2019).

Plant factory, as tech-intensive type of agriculture that features high yield, high efficiency, and high quality, is an advanced stage of the development of agriculture with controlled environment. Characterized by artificially controlled environment and factory operation, plant factory covers management of biological systems, engineering management, and IoT management (Yang and Zhang 2005a). Plant factory produces planned products all through the year with short crop growth cycles and little pollution. In such factories, the efficiency of land use and crop yield per unit area can be multiplied by stacking culture shelves vertically (Kozai and Niu 2016; Yang and Zhang 2005a). The extensive application of IoT technology marks a new round of development opportunities for plant factories and a symbol of smart agriculture in the twenty-first century. With IoT, thorough sensing and recognition, comprehensive interconnection, and deeper integration and analysis are possible, thus bringing intelligent control and decision of plant factories.

In this chapter, main components and types of plant factories are illustrated, and applications of IoT systems in plant factories are outlined, involving environmental control systems, CO_2 and nutrient solution supply systems, video monitoring and image transmission system, automatic logistics seedbed, intelligent robots, and computer remote automatic control system, so that readers may gain a comprehensive understanding of plant factory IoT.

11.2 Plant Factory Outline

11.2.1 The Concept of "Plant Factory"

The concept of "plant factory" was first proposed by Japanese scholars. Plant factory is a protected agriculture system that relies on computers to automatically and accurately control growing conditions, such as light, temperature, humidity, CO_2 concentration, and nutrient solution, thus enabling crop production all year long (Luna-Maldonado et al. 2016; Yang and Zhang 2005a). It mainly produces vegetables and fruits, flowers, herbs, and edible fungi. Plant factory is a tech-intensive mode of production that involves protected horticulture science, biotechnology, construction engineering, material science, information technology, and computer science (Yang and Zhang 2005b). It represents a new direction of agricultural development, and a focus in high-tech researches of global agriculture.

Compared to traditional agriculture production modes, the plant factory features the following advantages:

- More detailed production plan that can achieve annually balanced production
- Vertically stacked cultivation, which can significantly improve efficiencies of land and water use
- Higher crop yield per unit area
- Higher levels of mechanization and automation, lower labor intensity, and more comfortable working environment
- Safer and pollution-free products
- No or fewer influences from natural conditions like geography and climate
- Reduced transportation costs
- Advantages in producing rare, high-price, and nutritious plant products by combining with modern biotechnology

Plant factories could ramp up the efficiency of land use while keeping crops away from harsh climates; as a result, they have rapidly developed in Japan, the Netherlands, Denmark, Sweden, Norway, Austria, the United States, and Canada.

11.2.2 Main Components of a Comprehensive Plant Factory

In terms of space, a comprehensive plant factory is mainly composed of the following parts: seed laboratory, seeding room, seedling culture room, nutrient solution control room, cultivation room, air-conditioning room, central control room, cold storage, and delivery room. More specifically, the control system mainly includes airtight system, artificial lighting system, intelligent environmental control system, CO_2 supply system, circulation and sterilization system for nutrient solution supply, vertical cultivation system, video monitoring and image transmission system, computer control and remote controlling system, and intelligent transportation platform. Refer to Fig. 11.1 for a schematic diagram of a comprehensive plant factory.

11.2.3 Types of Plant Factory

11.2.3.1 Plant Factory with Artificial Lighting and Solar Lighting

Plant factory with artificial lighting and solar lighting is a factory mode that uses natural lighting in the daytime and artificial lighting at night or when it is clouded. This model, marked by low energy consumption, minimal climate impact, and stable crop production, is suitable for cultivating various flowering and fruiting plant species. However, this type of plant factory requires a large amount of electricity to cool down in summer, a season with sufficient sunlight and high temperature, and the stability of temperature is not as high as that of a totally enclosed plant factory

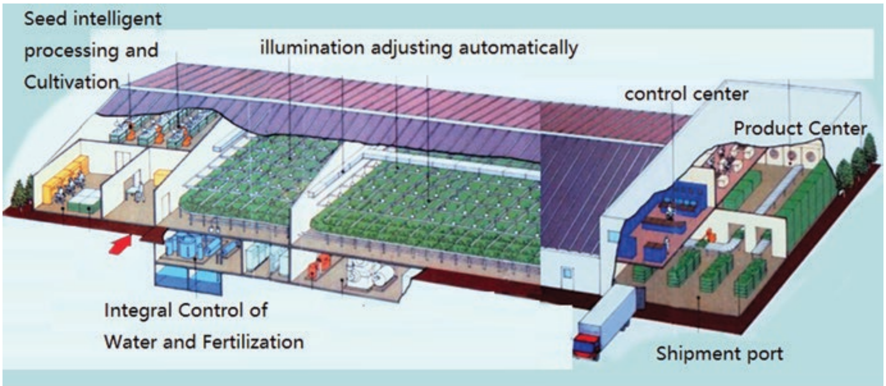

Fig. 11.1 Schematic diagram of a comprehensive plant factory. Note: The source of the diagram https://club.1688.com/threadview/46300110.htm

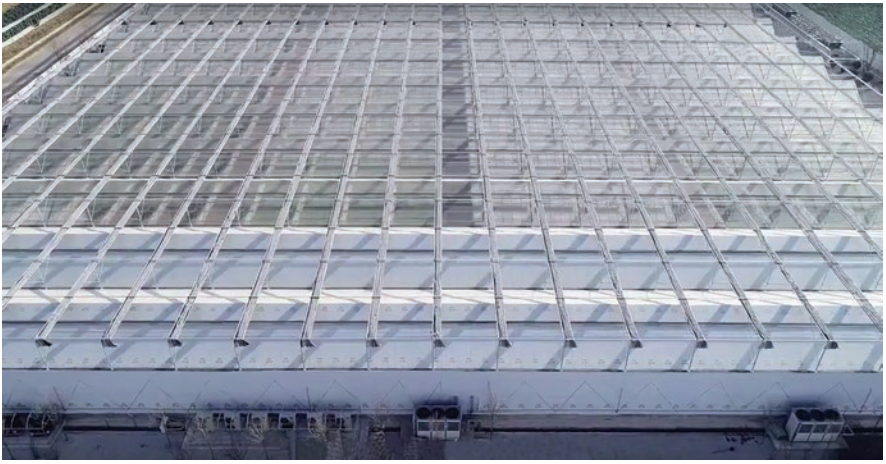

Fig. 11.2 A plant factory with artificial lighting and solar lighting. Note: The source of the photo https://v.qq.com/x/page/a0808pdr3uy.html?start=51

with artificial lighting. Currently, a large number of investors favor this type of plant factory (Fig. 11.2).

11.2.3.2 Plant Factory with Artificial Lighting

A plant factory that solely relies on artificial light sources (light-emitting diodes (LEDs), fluorescent lamps, high-intensity discharge lamps, and so on) features excellent air tightness and excellent insulation performance owing to its fully enclosed building structure. The indoor environment parameters and cultivation conditions (light, temperature, humidity, CO_2, nutrient solution) can be accurately

Fig. 11.3 Cultivation of a plant factory with artificial lighting

controlled, and the light-dark period can be adjusted accordingly (Yang and Zhang 2005b). Within such an environment, plants can grow steadily, and annually continuous production can be achieved. When compared with the plant factory that combines artificial lighting and solar lighting, this type of plant factory demonstrates a number of advantages, including higher planting density, higher energy efficiency, and higher utilization of water, CO_2, and land (Goto 2012; Graamans et al. 2018; Kozai 2013). Yet it also suffers from certain disadvantages, including higher early investment in facility construction and technical equipment and higher power consumption and operating costs (Graamans et al. 2018; Zhang et al. 2018). It is worth mentioning that the plant factory with artificial lighting is mainly used for cultivating seedlings, leafy vegetables, and mushrooms (Fig. 11.3).

11.2.3.3 Movable-Container Plant Factory

A movable-container plant factory is constructed using adiabatic plates for full isolation from the external environment. The variations in weather conditions have little effect on the climate of the cultivation space in a movable-container plant factory. The container plant factory is equipped with automatic environmental control system, lighting control system, and water circulation system to monitor environmental parameters, such as temperature, humidity, and CO_2 concentration inside

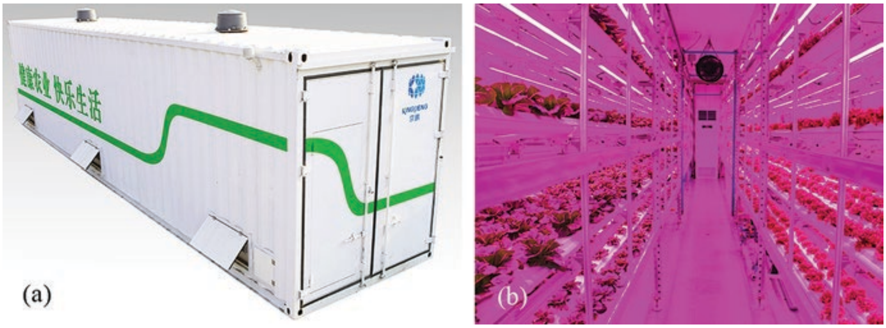

Fig. 11.4 A movable-container plant factory: (**a**) outside view, (**b**) inside view. Note: The source of the photo http://www.jingpeng.cn/page93?product_id=112

and outside the container. Furthermore, it allows automatic closed-loop control of environmental parameters, light parameters, and water pump. The factory is able to engage in all-weather artificial simulation and fully closed aseptic operation, making it suitable for cultivation research. The movable plant factory, as a high-strength container, adopts a modular design for easy lifting and transportation. It is capable of producing food anywhere, especially in ocean freighters, naval vessels, islands, border posts, and polar regions. Additionally, it also can be used as a base demonstrating and promoting plant factory technology (Fig. 11.4).

The plant factory constructed in the coldest polar regions ought to be well insulated; otherwise, it is difficult to build a stable cultivation space. In addition, solar or wind power generation systems are needed to provide the energy required for environmental control of the cultivation space. Currently, the University of Arizona in the United States has established this type of plant factory in the South Pole to supply fresh vegetables for staff working there.

11.2.3.4 Micro-Plant Factory for Households

The micro-plant factory is a fully closed and intelligent environment-controlled plant producing system that is suitable for households, allowing urban residents to experience the rural life by growing and picking vegetables at home. In such factories, vegetables are planted on multilayer hydroponic cultivation beds, where the nutrient solutions are provided on demand through an intelligent liquid supply system. The temperature, humidity, light, and wind speed in the system are adjusted by the intelligent environment-controlled system, while CO_2 is produced by humans. The intelligent monitoring system based on IoT makes it possible for the users to remotely monitor the micro-plant factory in real time via mobile phones and computers. The micro-plant factory comes with various cultivating forms and species. The size and the components of the cultivating box can be customized. One can create one's own special garden by planting leafy vegetables, mushrooms, flowers, or herbs. The micro-plant factory features multiple advantages, including small

Fig. 11.5 Micro-plant factory for households. Note: The source of the photo http://www.jingpeng.cn/page93?product_id=112

space occupation, ecological environment protection, extremely short distance between production and consumption, and considerable economic benefits. In the near future, the micro-plant factory will become an important model that urban residents could rely on to produce pollution-free vegetables. This type of plant factory also offers gorgeous views in four seasons, turning into safe and secure food on the table (Fig. 11.5).

11.2.3.5 Micro-Cabin Plant Factory

As a cultivation mode of producing plants in outer space using life support technology, the micro-cabin plant factory is an attempt by researchers in making plants grow normally in the weightless environment. This plant factory, designed to explore the practicability of plant cultivation on other planets, is still in an exploratory stage and has a wide development prospect, laying the foundation for human's next planet plan (Fig. 11.6). The United States has currently carried out cultivation experiments on the space station to solve the supply of fresh vegetables for astronauts.

Fig. 11.6 A micro-cabin plant factory designed for the space station. Note: The source of the photo https://mp.weixin.qq.com/s/D5-z3jsHujejUocARi5okA

11.2.4 IoT and Key Technologies of Plant Factories

11.2.4.1 IoT System Architecture of Plant Factories

The plant factory IoT system allows automatic operation, intelligent control, and standardized management of production relying on such IoT technologies as intelligent sensing, data transmission, automated control, scientific analysis, and decision. It consists of three layers, including the sensing layer, the transmission layer, and the application layer (Fig. 11.7). The functions of each layer are summarized below (Wang et al. 2018):

- The sensing layer mainly utilizes smart sensors, biochemical sensors, and cameras to sense environmental information of crop growth (temperature, humidity, nutrient solution, CO_2, and light) and physiological and ecological information of crops (growth properties, insects, and diseases).
- The transmission layer needs to build a three-level information transmission network of local control, factory monitoring, and intelligent agricultural IoT platform through wireless sensor networks, mobile communication networks, and wire communication networks, so that remote management and control of production can be achieved.
- The application layer mainly relies on environment simulation, intelligent control, intelligent decision, expert diagnosis, cloud computing, deep learning, big data, and other methods to be engaged in the sharing, exchange, and merging of information that is obtained from the sensing layer, thus achieving early-warning diagnosis, scientific decision, and intelligent management of various production processes of the plant factory.

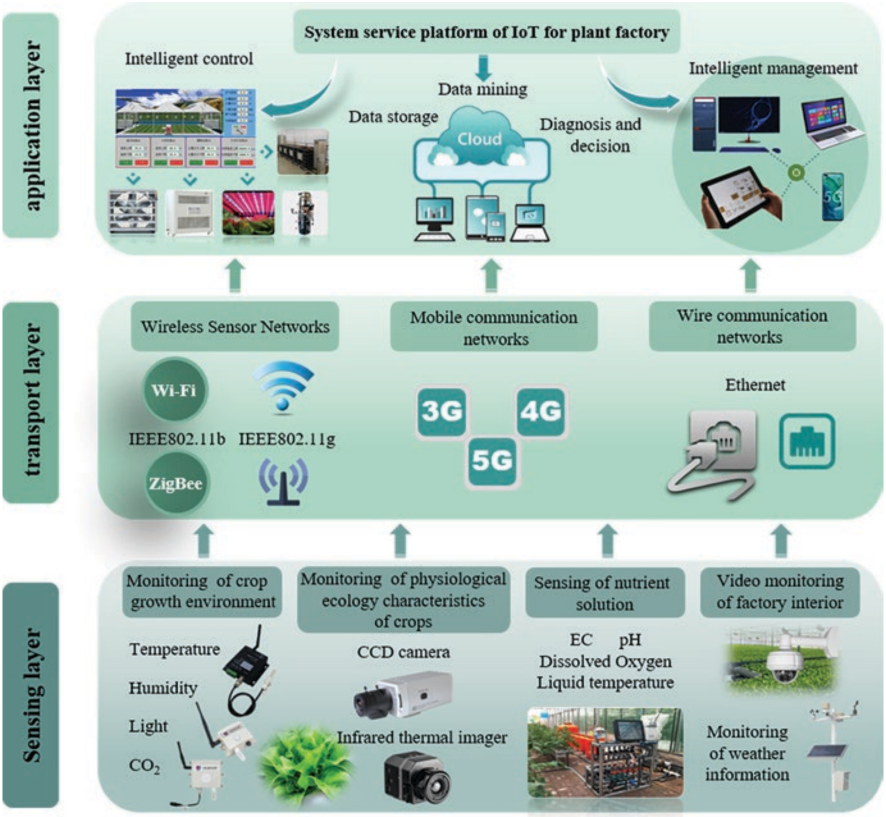

Fig. 11.7 IoT system architecture of plant factories

The aim of IoT system application is to offer comprehensive sensing of plant growth and environmental information and then to obtain the best growth conditions for crops through data processing, analysis, decision, and intelligent control. IoT systems can improve crop yield and quality and decrease costs like energy, water, fertilizer, and labor. As a consequence, high-yield, high-efficiency, high-quality, low-consumption, and safe and ecological production of plant factories can be achieved.

11.2.4.2 Key Technologies of Plant Factories

Sensing Technologies for Properties and Conditions of Plant Growth

Sensing technologies for properties and conditions of plant growth mainly adopt methods of smart sensors, machine vision, spectral analysis, and imaging to sense information of nutrient solution, greenhouse environment, and plant physiology and ecology.

Computer Simulation of Growth Environment

Thanks to computer simulation, the prediction and analysis of growth process and greenhouse environmental variations are achieved by mathematical modeling and computer simulation.

Information Transmission Technologies

Information transmission technologies, containing wireless sensor networks, mobile communication networks, and wire communication networks, aim to achieve remote supervision of crop production in plant factories and to ensure real-time stable information transmission. Additionally, it is required that a three-level (local control, factory monitoring, and intelligent agricultural IoT platform) network system of information transmission should be built.

Computer Intelligent Management

The methods adopted by computer intelligent management include deep learning, intelligent decision, cloud computing, and big data. Empowered by such adoptions, computer intelligent management achieves the analysis, diagnosis, and merging of the observed information involving data on plant, environment, cultivation management, production, and sales. It aims to offer rational decision-making and intelligent management of various production links of the plant factory.

11.3 Management of Plant Factories via IoT Systems

11.3.1 Supplementary Lighting Systems

As an energy source of plant required for life activities, light is also an important information medium that certain plants depend upon to complete the life cycle (Yang and Zhang 2005c). This makes the supplementary lighting system one of the most important environmental control systems in a plant factory. Factors such as light intensity, light quality (light spectral distribution or composition), photoperiod, and lighting mode significantly affect photosynthetic rate and plant growth (Harun et al. 2019; Wang et al. 2016; Zhang et al. 2015, 2018). Therefore, according to the light demand of different plants and various growth stages, it is essential that plant factories control light environment using IoT technology. The application of IoT technology can maximize photosynthetic efficiency while reducing energy consumption. Fluorescent lamps (FLS) are adopted extensively in plant factories with artificial lighting at an early stage due to their compact size (Shoji et al. 2013). High-pressure sodium lamps and high-pressure halogen lamps are also used in some plant factories as light sources. At present, most newly built plant factories use LEDs as supplementary light sources. LEDs are cold light sources that can be set close to the surface of leaves to supplement light, thus obtaining higher photosynthetic efficiency and making LED especially suitable for multilayer vertical cultivation systems.

The LED light source powered by a low-voltage power supply (from 6 to 24 V) is safer than that powered by high-voltage power supply. In addition, it saves nearly 80% of the energy consumed compared with an incandescent lamp with the same light efficiency. The changes in the LED current can achieve multicolor light emission of red, yellow, green, blue, and orange light. Studies have indicated that, instead of the full bands sunlight, plants only absorb light at specific wavelengths, such as red and blue light, for photosynthesis during the day, and that growth primarily takes place at night. A single-wavelength of LED can enhance photosynthesis in comparison with wide-band sunlight. Early artificial lighting contained large wavelengths of light other than red and blue, which led to high-power consumption. In particular, the infrared light was a thermal light source in early artificial lighting. Using LEDs at specific wavelengths to illuminate, the flowering and fruiting of plants can be adjusted, and their height and nutrition can also be controlled. As the chip technology further matures, the production of economical and practical LED light sources as well as the supporting control devices will be sure to play a major role in scaling up the adoption of plant factories (Fig. 11.8).

11.3.2 Intelligent Climate Control Systems

Plants could perform normal physiological activities and biochemical reactions only when under suitable temperatures. The temperature of environment and nutrient solution of the plant factory exerts significant effects on photosynthesis, respiration, transport of photosynthetic products, root growth, and the absorption of water and nutrients. Therefore, temperature control is essential for production within plant factories. In plant factories, temperature regulation is carried out by temperature sensors and automatic control systems. Temperature can be adjusted upward by a heating system, which generally consists of heat source, heating medium pipe, and radiator. The heat sources mainly include fossil fuels (coal, oil, and natural gas), electricity, waste heat, and geothermal resources, while the heating media include hot water, hot air, and steam (Yang and Zhang 2005c). Thermal-pump refrigeration systems and cold-water thermal storage systems are widely used for cooling in plant factories. Temperature control is currently one of the tasks that is accompanied with high operation costs in plant factories. To reduce costs, according to local conditions, wind power, solar power, and solar air conditioner can be used for heating and cooling. Moreover, geothermal resource and waste heat from power plants can be utilized for heating, making the system more economical (Togawa et al. 2014) (Fig. 11.9).

The relative air humidity is another critical environmental control parameter for plant factories. Humidity determines the water vapor pressure difference between the surface of leaf and the surrounding air; thus, humidity influences leaf surface evaporation. Low humidity results in large leaf surface evaporation, reduced inner

Fig. 11.8 Supplementary lighting system of LEDs

water and cell volume, low porosity, and fewer photosynthesis products. On the other hand, high humidity brings small leaf surface evaporation, excessive body water, and increase in stems and leaves, thus affecting the yield. Humidity also affects pests and diseases of plants. Under extremely high humidity (>90%), plants are susceptible to microbial attack, while under extremely low humidity, plants can be infected with powdery mildew and pests. Different plants have different requirements for the relative air humidity. Therefore, it is necessary to adjust the air humidity according to the type and growth stage of plants. In the automatic environmental control system, ventilation and heating are usually used for dehumidification, whereas spray and fan-pad cooling system are used for humidification.

11.3.3 Air Circulation Systems

When plants grow under moderate wind (3–4 m/min), the amount of CO_2 absorbed by the stomata increase significantly. Intelligent control of ventilation devices can effectively regulate the temperature, humidity, and CO_2 concentration in the cultivation room. Meanwhile, such control can make indoor gas distribution more uniform.

Fig. 11.9 Intelligent climate control systems

In particular, as CO_2 has a sinking property, convection ventilation can achieve uniform air supply on the surfaces of plant leaves. The air circulation system can significantly ramp up the seedling density to improve the utilization rate of space. In addition, it can also combine physical sterilization to achieve the sterilization of air in the cultivation space (Fig. 11.10).

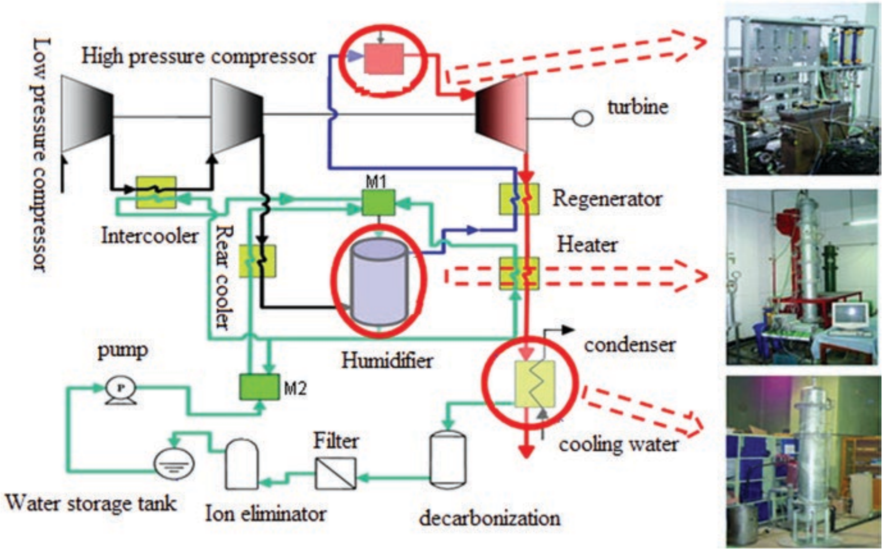

Fig. 11.10 Schematic diagram of an air circulation system

11.3.4 Nutrient Solution Circulation and Automatic Control System

The cultivation technologies of plant factories have evolved from solid substrate cultivation to hydroponics (NFT, DFT) and to aeroponic cultivation. Solid substrate cultivation is a culture mode that uses the solid substrate (gravel, rock wool, perlite, coconut bran, ceramsite, and so on) of water and fertilizer retention to support the root system of crops and provide certain moisture and nutrients for crop growth. The main supply method of nutrient solution is drip irrigation. Additionally, the nutrient solution supply system can be divided into closed-loop circulation system and open system. The difference between the two systems is that the former recycles the excess nutrient solution after absorbed by the substrate to the collection tank through the return pipe, while the latter discharges the excess nutrient solution out of the system through the drain pipe without recycling.

Hydroponics is a cultivation mode in which the roots of plants are immersed in the nutrient solution to obtain the water and fertilizer required for growth. There are, currently, three major cultivation techniques that are widely used, namely, deep flow technique (DFT), nutrient film technique (NFT), and floating capillary hydroponics (FCH). The nutrient solution layer of DFT is relatively deep. The plant is fixed by the planting tray, hanging over the solution surface, and the root system hangs down into the flowing nutrient solution. NFT allows the plant root system to spread flat on the bottom of the liquid tank, and the nutrient solution flows in a shallow layer from the upper end of the tank to the lower end. Aeroponic cultivation is a culture technique that uses a spray device to atomize nutrient solution into micron-level mist

Fig. 11.11 Nutrient solution circulation and automatic control systems

droplets and sprays them directly to the root system in an intermittent manner, so that the water and nutrients needed for plant growth can be provided. This technique addresses the contradiction of water and gas supply to the root system in hydroponics.

Charged with the task of delivering nutrient solution of appropriate formulation and concentration to each plant, the nutrient solution supply system is composed of a transportation system and a regulation-control system. The former consists of connected pipes, whereas the latter is composed of nutrient solution tanks, mother liquor storage tank, various detection probes, and a computer control system. Moreover, the nutrient solution supply system is also responsible for the regulation and control of EC value, pH, dissolved oxygen, and temperature of nutrient solution. The system offers solution that has sufficient dissolved oxygen, complete nutrient elements, and suitable pH and temperature to cultivated plants, so as to promote high-speed growth (Fig. 11.11).

11.3.5 CO_2 Supply Systems

CO_2 is an essential material for photosynthesis, which is why seemingly insignificant variations in CO_2 concentration can have major influence on the photosynthesis rate of plants (Kozai and Niu 2016). It can be inferred from this that CO_2 concentration is one of the major environmental factors in plant factories. CO_2 is quickly consumed in a limited cultivation space. If there is no external supply of CO_2, plants in the factory will grow poorly due to the lack of CO_2. The immense productivity of plant factories is inseparable from the compulsory supply of CO_2. The CO_2 supply system can maintain the CO_2 concentration required for photosynthesis of

Fig. 11.12 A CO_2 generator manufactured by ACME AGRO Group Limited

high-density plants in a plant factory, providing huge outputs of biomass. CO_2 supply devices currently used in greenhouses mainly include hydrocarbon-dependent CO_2 generators (burning hydrocarbons such as natural gas or kerosene to generate CO_2), carbonate-dependent CO_2 generators (using chemical reactions of carbonates and strong acids to generate CO_2), and CO_2 cylinders (Fig. 11.12).

11.3.6 Video Monitoring and Image Transmission Systems

The video monitoring and image transmission system, mainly composed of cameras, digital hard disks, computers, and control software, can carry out real-time online monitoring and video transmission. In order to achieve remote monitoring and diagnosis, cameras are generally installed in different areas of plant factories. These cameras are capable of 360° rotations and have variable focal lengths; thus, they can be counted on to observe the growth of plants from different angles. Installing this system allows easy remote diagnosis by experts. The experts can make clear observations of the stomata on surfaces of leaves and element deficiency diseases by a camera with an adjustable lens. The system can provide producers or researchers with a large amount of growth data for reference in making production decisions (Fig. 11.13).

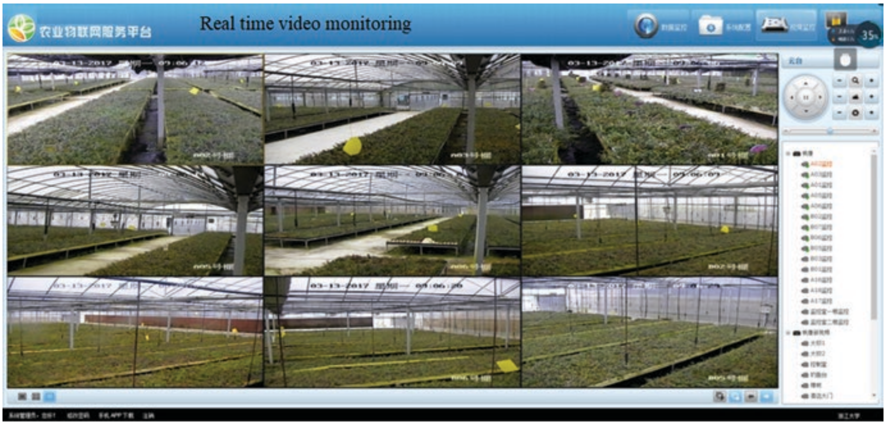

Fig. 11.13 Remote video monitoring platform

11.3.7 Automatic Logistics Seedbeds

Automatic logistics (movable) seedbeds are a major feature of an intelligent plant factory and an important part of the plant factory IoT system. Their emergence allows plant factories to achieve fully automatic production from sowing to harvesting, hence significantly saving investment on manpower. The logistics seedbed system is mainly composed of automatic movable platforms, single seedbeds, transverse guide rails, and longitudinal guide rails. The seedbed moves along longitudinal guide rails in the planting area driven by an automatic movable platform. When a new seedbed is pushed onto the rails, the previously placed seedbed will be pushed. Each set of transverse rails is equipped with two air-driven lifting rails. After the rails are raised, the seedbed can be moved along the lifting rails from the transverse rails to the planting area rails. The seedbed is lifted or dropped by the air cylinder and mechanical structure, so that the seedbed can switch the moving direction between the transverse guide rails and longitudinal guide rails (Fig. 11.14).

11.3.8 Intelligent Robots

As intelligent robot technologies mature, in future plant factories, most workers will be replaced by robots. A large number of production processes, such as grafting, transplanting, crop management, and harvest, will be done by robots. At present, relatively mature agricultural robots, including transplanting robots, grafting robots, cutting robots, logistics robots, routing inspection robots, and picking robots, that can be used in greenhouses and plant factories have been developed (Li et al. 2018; Zhang et al. 2019).

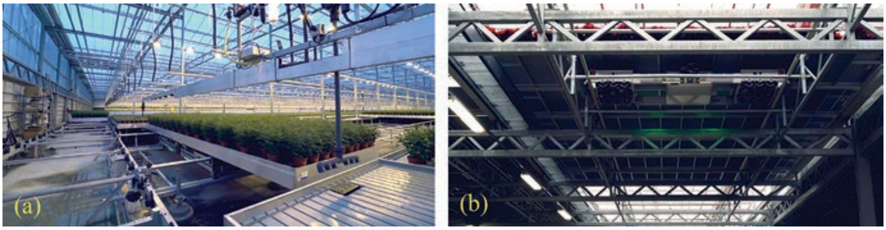

Fig. 11.14 Automatic logistics seedbeds: (**a**) side view, (**b**) bottom view

Japan and the Netherlands boast the most typical protected horticulture robot technology. At the end of the twentieth century, Japan developed a variety of production robots in the field of technology-intensive protected horticulture, ranging from grafting robots to cutting robots and harvesting robots. The Netherlands, as the global leader in greenhouse horticulture, rapidly developed robot technology based on the demand for precision management and precision control of greenhouses. For example, the cucumber picking robot developed by the Netherlands Institute of Agricultural and Environmental Engineering can reach the initial operating position within a short period of time, detect the accurate position and maturity of the cucumber through a vision system, and control the end effector to secure the cucumber and then separate it from the stalk (Hou and Xue 2019; Qi et al. 2019; Tu 2016; Wang 2015; Xu 2015).

11.3.8.1 Grafting Robots

As a kind of artificial vegetative propagation method, grafting technology is considered one of the most effective techniques to enhance the stress and disease resistance of fruits and vegetables and to achieve stable and high yield of crops. However, manual grafting suffers from such problems as high labor intensity, low efficiency, high cost, uneven levels, and low survival rate, which is why it fails to meet the needs of large-scale and standardized production of plant factories. Under this background, efficient grafting robots came into being.

The grafting robot is composed of a rootstock supply platform, a scion supply platform, a rootstock clamping and conveying manipulator, a scion clamping and conveying manipulator, a rotary cutting device, an automatic clamp feeding mechanism, a seedling conveying belt, a machine control system, and an air source. The working process of grafting robot can be described as follows (Chu et al. 2017):

- Seedling supply. The operator takes out the rootstock seedling and scion seedling from the trays on the left and right sides and places them on the corresponding supply stands. The two supply stands then rotate to send the rootstock and scion to the corresponding conveying manipulators.
- Seedling clamping and conveying. The manipulators for rootstock and scion conveying extend simultaneously and clamp the rootstock and scion from the supply

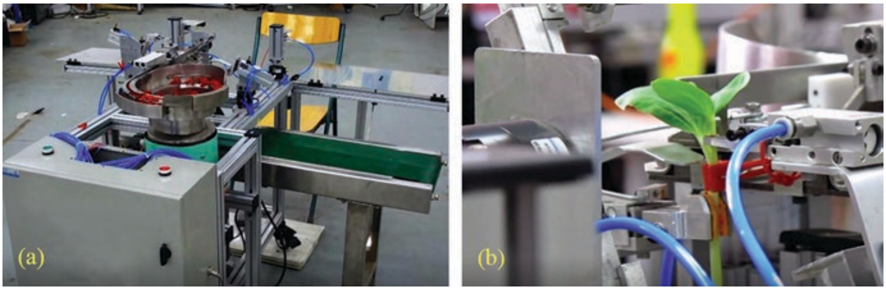

Fig. 11.15 A grafting robot: (**a**) appearance, (**b**) partial enlarged detail of grafting (developed by China Agricultural University, Key Laboratory of Ministry of Agriculture for Soil-Machine-Plant System Technology). Note: The source of the photo http://www.360doc.com/content/16/0604/22/30214551_565099707.shtml

stands. Then, after retracting, they rotate to send the rootstock and scion to the cutting position.

- Cutting seedlings. The rotary cutting mechanism drives the blade to rotate, cutting off the stalk of the scion and a cotyledon of the rootstock together with the growing point, thus forming a beveled cut.
- Combining and fixing. The rootstock manipulator and scion manipulator extend toward each other and bind the cutting surfaces of the two seedlings together. Then the automatic clamp feeding mechanism transports the grafting clamp to complete fixing.
- Seedling conveyance. The clamping claws of the rootstock and scion manipulators are opened, and then the grafted seedling falls onto the conveyor belt along the chute and is conveyed out of the machine.

The emergence of grafting robots has replaced the traditional manual grafting method that rely on bamboo sticks or blades, freeing people from monotonous seedling culture operations. The grafting robot is fast and efficient and saves labor costs. It is not only a high-quality and efficient modern agricultural production technology but also an integral part of the plant factory that cultivates melons (Fig. 11.15).

11.3.8.2 Transplanting Robots

The transplanting of plug seedlings refers to the process of transplanting seedlings from a high-density plug tray to a low-density one or a growing pot. It is a simple, time-consuming, labor-intensive, and repetitive operation, whereas manual transplantation is slow and inefficient. However, the transplanting speed could be faster by 4–5 times with improved stability using an automated transplanting robot.

The transplanting robot for plug seedlings is mainly composed of a mechanical arm, an end effector, a machine vision system, a computer control system, and a seedling tray conveying device. The main workflow is described below (Ren 2007):

- The seedling tray to be transplanted is located on the conveying mechanism, the seedlings suitable for transplanting is determined by the machine vision system, and the center position information of the seedling hole is obtained.
- The computer communicates with the PLC through a serial communication controller and transmits the position information acquired by the vision system to the PLC.
- The seedling tray continues to move to the grabbing area, and the position sensor signal is detected by the PLC.
- PLC controls the stepper motor to drive the mechanical arm to move above the seedling tray, and at the same time, it also controls the solenoid valve to push the cylinder. The seedlings are grabbed by the end effector at last.
- In the same way, the PLC controls the mechanical arm to move to the low-density plug tray and release the seedlings, completing a transplanting action at the end.

The high-speed automatic transplanting robot for plug seedlings are essential to reducing labor costs and improving the production capacity of plant factories (Fig. 11.16).

11.3.8.3 Intelligent Logistics Robots

Automatic Seedbed Transport Platforms

In a plant factory with vertical cultivation mode, an automatic seedbed transport platform can be relied on to transport the planted seedbed from the seedling culture workplace to the appointed cultivation shelf and then push it into the specific layer according to the computer instruction. During the harvest stage, the vehicle can move the seedbed from cultivation workshop to the harvesting workshop. Adopting the intelligent transportation platform, labor costs can be significantly cut, and the efficiency of bed transportation can be improved (Fig. 11.17).

Intelligent Transport Vehicles

The major components of an intelligent transport vehicle include a wheeled chassis, a layered loading frame, a visual navigation system, and an embedded control system. The four-wheel independent driving capacity gives the vehicle sound climbing

Fig. 11.16 Transplanting robot for plug seedlings: (**a**) grabbing seedlings, (**b**) planting seedlings. Note: The source of the photo https://v.qq.com/x/page/x0354mxfa9o.html

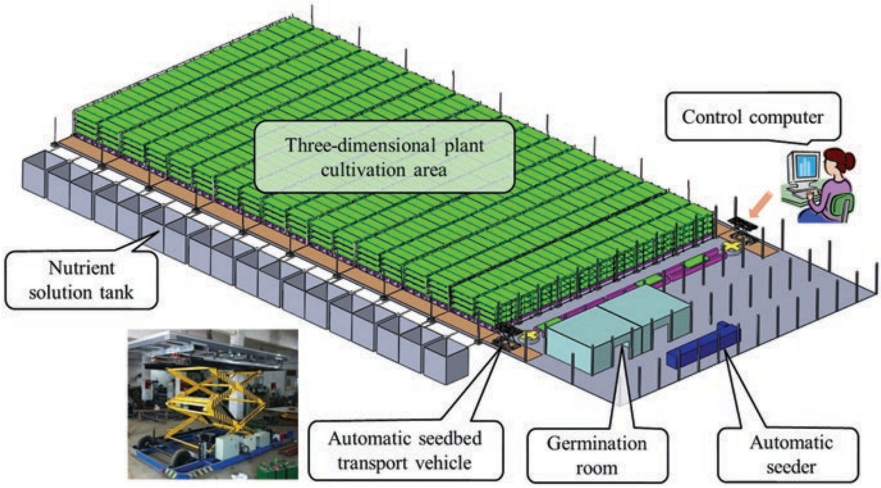

Fig. 11.17 Automatic seedbed transport systems. Note: The source of the photo https://wenku.baidu.com/view/5996321014791711cc79178f.html

and over-obstacle capabilities, as well as flexible steering performance. In addition, multi-sensor fusion of vision camera and ultrasonic sensor allows the vehicle to achieve autonomous navigation and obstacle avoidance. The intelligent transport vehicle generally comes with multiple operation modes, including manual software operation, remote control operation, and autonomous visual navigation operation (Fig. 11.18).

11.3.8.4 Intelligent Inspection Robots

During the growth of crops in plant factories, regular inspections are conducted to monitor the growth state of crops and the conditions of pests and diseases, to collect information on growth, to timely remove weak seedlings, to carry out pest and disease control, and to regulate the growth environment. The huge workload of management staff makes it difficult to reduce the labor cost of plant factory operations. Applying intelligent inspection robots, the growth state of crops is monitored in real-time via machine vision technology, and information on the growth environment is collected. All these data are then transmitted to the IoT cloud platform, which proceeds with environmental regulation and control of plant diseases and pests based on the information. The research and development of intelligent inspection robots will contribute to the creation of intelligent control and big data management of plant factories and reduce labor input. Moreover, intelligent inspection robots are critical for promoting the commercialization of plant factories.

An intelligent inspection robot is primarily composed of a computer control system, a movable platform, navigation and positioning system, high-definition camera group, environmental monitoring sensors, and image data transmission systems.

Fig. 11.18 An intelligent transport vehicle developed by Suzhou Agribot Automation Technology Co., Ltd

When working in a greenhouse or a plant factory, the inspection robot autonomously moves along the crop cultivation lines and collects environmental parameters such as temperature, humidity, CO_2 concentration, photosynthetic radiation, and wind speed, together with three-dimensional fixed-point images of crops through multiple sets of cameras. The images are analyzed by the analysis software; consequently, the plant height, fruit color, and pest and disease status are intelligently identified. The fruit ripeness can be determined by comparing the objective color values with the standard color values. In addition, the fruit-bearing conditions can be used to predict yield, thereby assisting production management (Fig. 11.19).

11.3.8.5 Fruit and Vegetable Picking Robots

Picking is one of the most time-consuming and labor-intensive links in the production processes of fruits and vegetables. The labor costs required in this part accounts for about 40–50% of that required by the entire cultivation process. Due to the large-scale, structured, and standardized cultivation, plant factories are especially suited for the adoption of robotic picking, which significantly reduces labor and production costs. Thanks to the developments of vision sensor technology, multi-sensor

Fig. 11.19 An intelligent inspection robot. Note: The source of the photo http://www.taihainet.com/news/fujian/gcdt/2019-06-18/2274873.html

fusion technology, and AI technology, currently, picking robots applied for fruits and vegetables, such as tomatoes, cucumbers, bell peppers, and strawberries, have come into being.

The major components of the picking robot for fruit and vegetable include a computer control system, cameras, a picture processor, a manipulator, a mechanical arm, an end effector, and a walking mechanism. While working in a plant factory, the robot can obtain accurate information relating to the size, color, and shape of the fruit through cameras. Additionally, it can determine the maturity of fruits and create three-dimensional spatial information of the object to be harvested. More specifically, relevant signals are transmitted to the manipulator to guide the mechanical arm and the end effector to complete the tasks of grasping, cutting, and recycling. The intelligent picking robot can achieve autonomous navigation, automatic identification, and unattended picking operation. Its success rate of picking can reach more than 90%, which means that it can solve the complex problems of fruit and vegetable harvesting. Some picking robots are even equipped with lighting device and thus can work during both daytime and night. Currently, picking robots are still in the experimental stage and have not been put into practical application on a large scale. As signature products of smart agriculture, they are expected to be commercialized and extensively adopted in plant factories in 5 years (Fig. 11.20).

Fig. 11.20 A picking robot based on binocular stereo vision (developed by China Agricultural University, Key Laboratory of Modern Precision Agriculture System Integration Research, Ministry of Education)

11.3.9 Computer Remote Automatic Control System

The computer remote automatic control system is commonly known as the brain of a plant factory, and each of the aforementioned systems works to serve this system. Relying on the system, one is able to monitor and control all environmental factors and cultivation factors with plant factories. For example, when the temperature sensor detects a value that exceeds the maximum limit, the computer will issue a command to turn on the cooling system for reducing the temperature, and when the temperature drops below the minimum limit, the computer will send an instruction of turning on the heating system to increase the temperature. The same applies to the control of other environmental/cultivation factors, such as humidity, light, and nutrient solution. The relative stabilities of those factors are achieved through closed-loop feedback control of the system. After installed, the automatic control systems can also be connected to a computer to implement remote control using software. The technicians can complete all operation parameters settings, expert mode switching, and image processing in the office.

11.4 Research Progress on IoT Technologies in Plant Factories

In recent years, IoT technologies have been extensively adopted in greenhouses and plant factories for environmental regulation, monitoring of plant physiology and ecology, intelligent management of cloud platform, and rational decision-making. Researchers have carried out a large number of application studies of greenhouse IoT system on the acquisition and transmission technologies of information relating to growing environment, simulation of the growth process, and environmental control (Li and Wang 2014). In addition, machine vision, artificial intelligence, cloud computing, big data, and other information technologies have also been introduced into IoT systems of greenhouses and plant factories (Tzounis et al. 2017; Wang et al. 2018).

In terms of sensing and transmission of greenhouse environmental information, the environmental control system with wireless sensor networks has become the prime choice of greenhouse IoT systems (Ojha et al. 2015; Rodríguez et al. 2017; Talavera et al. 2017). Concerning environmental intelligent regulation, Harun et al. (2019) proposed a new approach of using IoT technology as a remote monitoring system to control indoor climate conditions. In order to collect real-time data of the plant experiment and monitor the environmental parameters, an intelligent embedded system was developed to achieve automatic control of LED parameters, including spectrums, intensity, and photoperiod. To stabilize the production environment of salad-cultivating plant factories, Deng et al. (2018) developed a highly valid kinetic model using system dynamics and experimental data, and the pattern of optimal closed-loop control of temperature, aerating rate, and light intensity were determined based on the gradient of stored-energy function of the salad-cultivating plant factory (derived from Hamilton-Jacobi-Isaacs equation). Digital and real-time simulation results demonstrated that the closed-loop control system could overcome internal changes and external disturbances to stabilize the plant factory at an operating point and maintain sound salad yield.

In order to effectively monitor the growth of crops, machine vision technology based on the capturing and processing of image and video is utilized in plant factories and greenhouses. Chen et al. (2016) designed an automated weight measurement system, comprising a weight measurement device and an imaging system, for hydroponic plants of a plant factory. The system continuously measures the plant weight throughout the entire growth period without impacting growth. Moriyuki and Fukuda (2016) developed a high-throughput diagnosis system based on the measurement of chlorophyll fluorescence for a commercial plant factory. The diagnosis system depends on a high-sensitivity CCD camera and an automatic transferring machine to capture chlorophyll fluorescence images of seedlings. Machine learning is then utilized to accurately predict plant growth based on leaf size, amount of CF, and circadian rhythms. This system can be used as advanced seedling diagnosis technology to identify and cull low-grade plants at an early stage, which is why it plays a major role in avoiding major losses. Based on machine vision, Franchetti et al. (2019) proposed a novel method, combining 3D reconstruction, leaf segmentation, geometric surface modeling, and deep network estimation, for the accurate prediction of the phenotype features of plants, including height, weight, and the size of leaves. A greenhouse monitoring system for disease recognition of leaf vegetables was constructed by Ma et al. (2015a, 2015b, 2017) using the environmental information observed by sensors and the video information monitored by cameras. Liao et al. (2017) created an IoT system that can simultaneously monitor environmental factors of the greenhouse and the growth status of *Phalaenopsis*. Liao also proposed an image processing algorithm based on the Canny edge detection method, the seeded region growing method, and the mathematical morphology to estimate the leaf area of *Phalaenopsis*. Monitoring the growth of *Phalaenopsis* may be conducive to obtaining optimal cultivation conditions.

Cloud service technology is particularly important to the real-time, remote monitoring of environment and crops. On-site sensors obtain various types of information and transmit them to the cloud platform that performs data management and uses artificial intelligence, data mining, simulation models, expert knowledge, and other technologies for decision services to achieve intelligent management and control of greenhouses (Wang et al. 2018). Cui et al. (2015) built a cloud-computing greenhouse IoT service platform that provides intelligent environmental monitoring, cloud storage, and analysis of large-scale data, real-time cloud early warning, and personalized cloud services. Çaylı et al. (2018) developed a cloud-based, low-cost environmental monitoring system in greenhouses via open-source hardware to monitor climate data of agricultural practices for small businesses and rural areas.

Spectrum analysis and imaging technologies have evolved into major technical detection methods in agricultural research, production monitoring, and plant phenotypes, such as estimating leaf water content (Yi et al. 2013), assessing crop health (Liu et al. 2010), detecting pests and diseases (Mei et al. 2014; Weng et al. 2018), and identifying seed quality (Sun et al. 2019). As spectrum analysis technologies, picture processing technologies, and spectrum online detection technologies progress, in the future, spectrum analysis and imaging technologies will become the key monitoring technologies to improving the IoT systems of plant factories.

11.5 Summary

Currently, the plant factories have been recognized as the most advanced stage of protected agriculture development all around the world. Breakthroughs in artificial-lighting cultivation technology and IoT technology of plant factories have made crop production in non-arable lands, including skyscrapers, deserts, Gobi, islands, ships, and polar regions, come true. Therefore, plant factory is considered a critical way to solve the problems of the twenty-first century, ranging from population expansion and resource shortages to food security and environmental pollution. It is also viewed as an important means to achieve food self-sufficiency in future space engineering and space exploration.

Nevertheless, plant factories still face problems like high initial investment in equipment, high operating costs, weak market competitiveness, and insufficient profit. As such, progress on the industrialization of plant factory has been slow. In recent years, interested institutes and enterprises have focused on improving the automation and intelligent operation of plant factories and reducing running costs through the construction of intelligent environmental control systems and IoT system. In particular, they attach importance to the research of LED light sources, the development of efficient nutrient solutions and intelligent robots, the utilization of clean energy (solar energy, geothermal energy, waste heat, etc.), and the application of big data analysis and scientific decision. The commercial prospects of plant factories will be increasingly exciting, as intelligent environmental control systems improve, energy and labor costs decrease, and the market positioning of products become clearer.

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