REVIEW ARTICLE

Prospects and challenges of novel agricultural robots in vertical farming: A review

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Vertical Farming System (VFS) is an innovative method of agricultural production that combines crop cultivation with construction, often in indoor environments such as buildings, warehouses, or other urban structures, so that the produce from vertical farms can be supplied to city dwellers with reduced transport costs and carbon emissions. Vertical farms feature vertically stacked, three-dimensional planting racks, where each level can be planted with the appropriate crop, and where all environmental and crop growth factors are monitored and controlled. Vertical farms can help to solve the current food and vegetable supply and supply chain problems caused by the increasing global population, global influenza and growing regional conflicts. VFS are highly automated and therefore robots of all types are used in them, from planting, fertilizer application, growth monitoring, harvesting, and transporting. Many robotic systems have been designed and developed by researchers around the world for various scenarios in agricultural production, and many robots are suitable for use in VFS. This paper provides an overview of agricultural robots that have been used by researchers around the world over the past 5 years to detect or monitor the agricultural environment and crop growth data, as well as robots that perform agricultural operations, and some agricultural robots that have not been developed for VFS but have the potential to be used in VFS through simple modifications. The results of the study may allow VFS practitioners, producers, and other stakeholders to learn more about the current level of robotics development in the industry and to adopt more automated production methods to improve the efficiency and economic benefits of VFS.

Keywords: sustainable environmental development; vertical farming system (VFS); efficient food production; farm robots; sensor.

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Introduction

The agricultural crisis

Sustainable Development Goals (SDGs) were put forward at the UN General Assembly in 2015 including 17 goals and the second of which is Zero hunger [1]. However, given the current state of the world, it will be very difficult to achieve the goal by 2030. World food security is affected by many factors [2]. When we look at the future of the world as bright, and our world is not going to be destroyed by sudden large-scale wars or diseases or natural disasters, then as the average age of the world's population continues to increase with the advancement of medical technology, and as the survival rate of babies and children increases dramatically due to improved medical and sanitary conditions and better diets, this inevitably results in the world's population Inevitably, this has led to continued growth in the world's population [3]. According to the United Nations, the world population is projected to grow to around 8.5 billion by 2030, and further to around 9.7 billion by 2050 [4], and it is expected that food production will have to increase by between 100 and 110 per cent between 2005 and 2050 to meet the growing demand from population growth. In contrast to this population growth, however, arable land per capita is declining, with models estimating that by 2050, the amount of arable land per capita will be only one-third of what it was in 1970 [5]. At the same time, along with economic and technological development, urbanization is intensifying, metropolitan areas are expanding, and the urban population will continue to grow, with the proportion of people living in cities expected to increase from 55% to 68% a large population growth that will create a huge increase in demand for agricultural products [6, 7].

Not only does the production of agricultural products face enormous problems, but the transport of agricultural products also faces many problems. Today's world is a highly globalized world, and agricultural products also have a globalized supply chain that is dependent on all regions of the world. Due to various reasons such as seasons, climate, population density, production capacity, *etc*., many countries import their own agricultural products from other countries, and some of the countries that are highly dependent on food imports are the Middle Eastern countries and the countries in North Africa (Sudan, Yemen, and Egypt). Therefore, the safe transport of agricultural products around the world is crucial to achieving the goal of zero hunger [8]. However, in today's world, regional conflicts continue to intensify, and small and medium scale wars occur frequently, these unstable factors have led to food not being able to be transported safely and efficiently around the world. For example, the war between Russia and Ukraine, in which attacks were made on grain ships and grain silos in ports, has resulted in large quantities of agricultural products produced in Ukraine not being able to be safely transported to countries around the world, thus leading to high food prices globally, which, according to the International Food and Agriculture Organization (FAO), reached 159.3 points in March 2022, the highest level since 1990, according to the Food Price Index (FFPI) [9]. Also affecting food transport are global influenza, such as COVID-19 in recent years. With the outbreak of global influenza (COVID-19), there were considerable restrictions at ports and airports in various countries and regions during the outbreak because of its extreme transmissibility, and these greatly hindered the global movement of food and fruits and vegetables [10]. Even within a country, the transport of agricultural products between the various regions of the country was considerably hampered by the COVID-19 outbreak, and with this collapse of the supply chain, the population had to rely on snapping up agricultural products for their daily lives as there was not an adequate supply of agricultural products [11, 12].

Vertical farming system (VFS)

In response to the shortage of agricultural products, scientists have approached the problem from several different directions. Method 1: Increase the unit yield of agricultural products (Table 1), for example, using genetic engineering breeding or space breeding or cross-breeding and other breeding methods to obtain seeds of agricultural products with higher yields [13]; using high-density planting techniques, planting more crops (single varieties or a combination of varieties) on a limited amount of land [14]; using highly efficient irrigation techniques and organic fertilizers to increase the yield of crops per unit of land area [15]; and using high-tech agricultural techniques such as precision agriculture or Vertical Farming and other high-tech agricultural techniques to increase crop yields per unit [16]. Method 2: Increase the area under cultivation of agricultural products (Table 2), for example, develop sustainable agriculture to reduce soil erosion and excessive consumption of water resources [17]; develop urban agriculture, using unused land or rooftops for cultivation of agricultural products in or around cities urban agriculture; develop salt-tolerant varieties using advanced breeding

Table 1. Technologies to increase per unit yield.

Technology category	Technology description
Precision Agriculture Technologies	Soil and crop monitoring systems, satellite imaging and remote sensing, GPS navigation, automated and smart irrigation systems, drone monitoring, agricultural robots
Genetic Engineering and Biotechnology	Genetically Modified (GM) crops, molecular breeding, CRISPR gene editing, microbial fertilizers and biopesticides
Hydroponics and Soilless Cultivation Techniques	Hydroponic systems, aeroponic systems, tidal cultivation systems
Vertical Farming	Multi-layer cultivation systems, indoor LED growth lighting, environmental control systems
Agricultural Information Technology	Agricultural Information Management Systems (AIMS), big data analytics in agriculture, Internet of Things (IoT) for agriculture
Mechanization and Automation	Smart tractors, automated planting and seeding machines, automated picking and harvesting robots
Integrated Pest Management (IPM)	Biological control methods, disease and pest resistant crop varieties, precision application of pesticides
Soil Management and Fertilization Techniques	Soil conditioners, organic fertilizers, slow-release and controlled-release fertilizers
Crop Modeling and Decision Support Systems	Crop growth models, climate models, Decision Support Systems (DSS)
Climate-Smart Agriculture	Crop varieties adapted to climate change, microclimate management techniques, climate adaptability planting strategies

Table 2. Methods to increase agricultural land area.

Method category	Method description
Land Reclamation and Improvement	Land leveling, soil improvement
Irrigation Technology	Construction of irrigation systems, improved water resource management
Vertical Farming	Utilizing vertical space for multi-layer cultivation
Greenhouses and Controlled Environment Agriculture	Greenhouse construction, extending the growing season
Land Reclamation	Restoring degraded land, improving polluted land
Desalination and Saline Land Transformation	Providing irrigation water through desalination, transforming saline lands
Urban Agriculture and Rooftop Farming	Conducting agricultural activities in urban spaces like rooftops and abandoned areas
Agroforestry and Multi-tier Farming	Planting crops under forest canopies, implementing multi-tier cultivation
Ecological Restoration and Eco-Agriculture	Increasing land area through ecological restoration projects
Land Policy and Planning	Increasing agricultural land through land planning and policy incentives
Agricultural Mechanization	Improving land cultivation efficiency with modern agricultural machinery
Biotechnology	Cultivating stress-tolerant crops to increase cultivable land area

techniques, so that agricultural products can be cultivated on a large amount of saline land that would otherwise be unsuitable for cultivation of agricultural products [18].

Table 3. Advantages of vertical farming compared to traditional agriculture.

Advantage category	Advantages of vertical farming compared to traditional agriculture
Resource Efficiency	Efficient use of space; Water conservation; Optimized energy use; Reduced chemical usage
Yield & Efficiency	Maximized yield; Year-round production; Rapid iterative improvement; Enhanced crop quality
Environmental Impact	Reduced land degradation; Eco-friendly practices; Mitigation of urban heat island effect; Provision of ecosystem services
Economic & Social Benefits	Reduced transportation costs and carbon footprint; Increased job opportunities; Improved food security; Quick market response capabilities
Technology & Innovation	Data collection and analysis; Promotion of technological innovation; Application of automation and robotics technology
Community & Education	Urban greening and beautification; Education and community engagement; Platform for agricultural technology education and research
Food Safety & Quality	Enhanced food safety; Crop diversity; Reduced supply chain risks
Risk Management	Reduced weather-related risks; Controlled environment minimizes weather variability; Decreased incidence of crop diseases and pests
Labor & Management	Labor savings; Automated management; Data-driven decision-making with precision agriculture technology
Animal & Plant Welfare	Improved welfare for plants and animals; Precise control over growth conditions

Vertical Farming is an innovative approach to agricultural production that combines crop cultivation with construction, often in indoor environments such as buildings, warehouses, or other urban structures, so that the produce from vertical farms can be supplied to city dwellers with reduced transport costs and carbon emissions. Vertical farms have a high utilization of space as they are set up with multiple levels of planting racks, each of which can be used to grow a specific crop [19]. In the vertical farm, a reflection of precision agriculture, in the vertical farm system, all the crop growth factors, such as light intensity and time, temperature, carbon dioxide concentration, humidity, water, nutrients, etc. are precisely controlled, and real-time monitoring of the crop growth status and growth environment, the monitoring data into the crop growth model, can predict the crop yield, as well as Crop maturity time and other data. Many agricultural robots are used in this process, and part of the process can be fully automated [16]. In addition to the benefits mentioned above, vertical farms have distinct advantages over traditional agriculture in many ways, including resource efficiency, yield and efficiency, environmental impact, economic and social benefits, technology and innovation, food safety and quality, community and education, risk management, labor and management, animal and plant welfare (Table3) [16].

Methods

In response to the current shortage of agricultural commodities and the risk that the fragile chain of agricultural commodities could be destroyed by sudden regional conflicts and pandemics. Moreover, rapid global urbanization has led to the growth of large cities and the formation of mega metropolitan areas, such as Tokyo, New York, and Beijing, which are all expanding [20]. The development of a new type of agriculture is therefore crucial to facing the challenges of the future [21]. Vertical farms, a new type of agriculture, are currently growing rapidly and attracting numerous researchers from around the world to study various aspects of it. One of the major issues facing vertical farms is economic efficiency, and one way to increase the economic efficiency of vertical farms is to increase the level of automation in vertical farms by using a large number of robots to perform a large number of tasks that arise throughout the life cycle of agricultural products [22]. Therefore, the focus of this review was on the study of various types of robots in vertical farms to answer the following questions:

(1) what is the current status of development of various types of agricultural robots?
(2) what are the current prospects for the use of various types of agricultural robots in vertical farms?
(3) what other aspects are worth exploring in the robotic systems that make up vertical farms?

Currently, more and more researchers are joining in this promising research topic of vertical farms, and a lot of experimental and theoretical studies have been conducted on many aspects of vertical farms, and the research results of the researchers have been published in the form of journal papers, conference papers, professional reports, and books. In order to answer the above three questions, we need to review the scientific outputs of previous researchers who have done research on the relevant content and answer the three questions posed in this Review by collating as well as analyzing this literature. The criteria for literature selection in this study were as follows, encompassing six key points.

(1) Journal articles, original papers, review papers, conference papers
(2) Periodic publication:2019-2024.
(3) Potential answers to research questions.
(4) Scopus indexed articles by listing title, affiliation, year, source, abstract, and quartiles (Q1-Q4 and Non-Q).
(5) Research in the literature has focused on research on agricultural robots for use or potential use in vertical farms, including agricultural data monitoring or inspection robots, agricultural manipulation robots, and general-purpose agricultural robots.
(6) Publications are written in English.

The databases used for this Review were Web of Science(https://www.webofscience.com/wos/woscc/basic-search), Scopus (https://www.scopus.com/home.uri?zone=header&origin=), Proquest (https://www.proquest.com/), and Elesvier (https://www.elsevier.com/).

However, finding and selecting the right literature is a challenge because vertical farms are not yet a mature research field and the definition and naming of vertical farms are not yet uniform. For example, some people call it "indoor farm", "precision farm", "farm 4.0", "smart urban vertical farm (SUVF)", and so on, and many of these articles have different names for vertical farms. These articles with different names for vertical farms also contain a lot of actual research content that is related to the issue under discussion, therefore, in the literature search, the keywords used in the database search were (("Farming OR Agriculture") AND ("Vertical agriculture "OR" Vertical Farming" OR "Intelligent Farming" OR "Smart Agriculture" OR "Precision Agriculture" OR "Smart Farming" OR "Greenhouse" OR "smart urban vertical farm "OR“ Internet of Things” OR “IoT") AND ("Robot" OR "Mechan" OR "Manipulator" OR "Manipulator arm" OR "Manipulator claw" OR" End effector")). In the process of reading and analyzing the literature at a later stage, literature that was not related to the content of this paper was eliminated.

Vertical Farming Robot

Research in agricultural robotics covers the entire spectrum of agricultural activities, from planting crops, caring for their health, applying fertilizer and watering, and finally harvesting the crops. Especially in vertical farms, the growing environment and the growth cycle of the crops are monitored and regulated, and each life cycle of the crops in the vertical farms is served by the corresponding agricultural robots (Figure 1) [23, 24]. Robots used in vertical farms are mainly divided into three categories. The first category is used to detect or monitor crops, including: crop growth status, Crop Phenotyping, nutritional requirements, pests and weeds, Leaf disease,

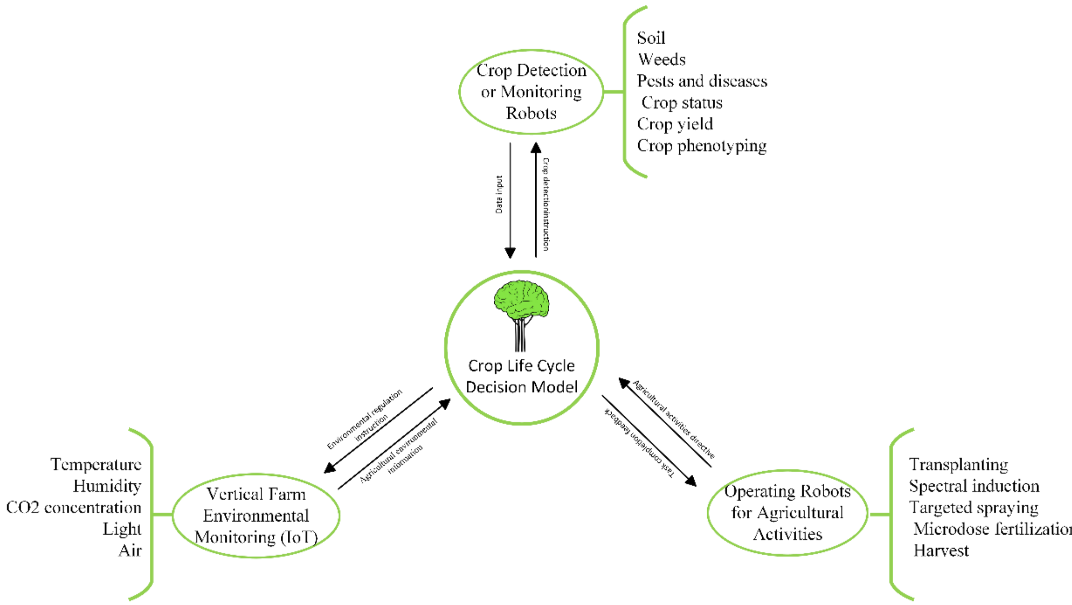

Figure 1. Vertical farm task flow.

crop yield, *etc*. The second category is used to perform operations, including seeding, weeding, fertilizer, directional spraying, changing light, harvesting, transport, *etc*. The third category is similar to industrial robots. The third category is a universal operating platform similar to an industrial robot or industrial machine tool, where the robot's end-effector can be replaced with the end-effector required for the task, depending on the task the robot is performing [25, 26].

Vertical farms are a type of indoor farm. To maximize space utilization, in vertical farms, the distance between rows of crops is shorter, and vertical farms are layered with high total heights and low heights between layers, which are unique to vertical farms. Therefore, many agricultural robots that are currently used in outdoor environments cannot be used in indoor farms such as vertical farms due to the limitations of the working environment of vertical farms [19]. Later in this paper, the review of various types of agricultural robots will focus on agricultural robots that can be or have the potential to be adapted for use in vertical farms.

1. Detection or monitoring of agricultural robots

Vertical farming is also a practical application of precision agriculture, in which the growth of crops is required to be precisely controlled. But throughout a crop's life cycle, it grows from a seed or seedling to blossom to fruit, and eventually the fruit is harvested by humans. Throughout this life cycle, the crop develops many different characteristics. These characteristics need to be accurately measured and stored in the form of data, which is transferred to the model constructed for the crop to derive the next agricultural operation that needs to be carried out. Therefore, various types of detection or monitoring agricultural robots are a must throughout the operation of a vertical farm [27, 28]. These robots not only need to face the complexity of the vertical farm environment, but also need to monitor various things that can affect the healthy growth of crops or reflect their biological characteristics [29]. For example, environmental data such as temperature, humidity, light, CO_2 concentration, *etc*. will have a direct impact on the growth cycle and physiological processes of the crops [30]. The conductivity and pH of the soil or petri dish or culture solution will have a direct impact on the growth cycle of the crops and the quality of the

Table 4. Detection or monitoring robots for vertical farms.

Reference	Application objectives	Type of sensors	Result description
[35]	Soil condition testing	Ultrasonic Sensors, Temperature and Humidity Sensors, Soil Moisture Sensors, GPS	When the data returned from the soil moisture sensor shows that the soil humidity is below 60%, the pump will be activated regardless of the air humidity rivalry; when the air humidity is below 70%, the pump will be activated regardless of the soil humidity condition.
[36]	Soil testing	Magnetometer GPS Ambient sensor Temperature sensor Moisture sensor	The soil is extracted by a hollow core auger and then the data is acquired in conjunction with the appropriate sensors installed, generating a soil test report for the area after a site has been tested.
[37]	Soil conductivity test	Electromagnetic Interference (EMI) sensor CMD-Tiny (GF Instruments) conductivity sensor	The Eca data of the soil is measured using small EMI sensors, from which information on the spatial distribution of water within the soil can be deduced for precise irrigation.
[38]	Weed detection	Optical sensor	The image information of the agricultural environment was obtained using an optical sensor and then the trained YOLO5 model was used to detect weeds with a speed of 0.02 s per image.
[39]	Weed detection	Optical sensor	Developed a new CVDL-WDC technique that enhances the correct identification of plants and weeds in agricultural environments.
[40]	Proximal detecting invertebrate pests	Wild-angle cameras of smartphones (20 cm-50 cm)	The acquired image information was analysed using the M5C model with an overall accuracy of 98.78%.
[41]	Pest detection on kale farms	Webcam, USB-RS485 sensor	The image information obtained from Webcam is passed into the pest classification model and an improved GoogleNet model is proposed which improves the model performance, shortens the runtime and reduces the file size compared to the original model.
[42]	Crop growth status monitoring	Logitech c920	Plant growth status was collected every half hour using an image sensor and the images were fed into a plant growth status prediction model.
[43]	Strawberry production monitoring	Intel® RealSense™ D435i depth camera	A robot that combines AMR and MRP is proposed, which can be combined with a depth camera to obtain temporal-spatial phenotypic data within the whole strawberry factory. when the travelling speed of MRP is 0.2 m/s the error rate of strawberry yield monitoring is 6%. The error rate of monitoring is 6.26%.
[44]	Crop Phenotyping	Intel RealSense D435i cameras Intel RealSense L515 LiDAR camera Fluorometers	The robot is detected by multimodal sensors and records RGB, NIR and depth images of the crops, which are then combined with motion information to obtain 3D visualisations.
[42]	Plant Phenotyping	depth camera (Intel RealSense SR-300)	Rapid construction of complete plant phenotype datasets using three depth cameras combined with the NBV planner to compute next-best viewpoints
[45]	Phenotypic measurements	VNIR, ToF cameras, laser, profilometer, PAM). fluorometer	The robot provides comprehensive measurements of plant growth parameters through the cooperation of multiple sensors and optimises the positioning and timing of plant phenotypic measurements

Table 5. Agricultural operation robot for vertical farming.

Reference	Application objectives	End effector	Result description
[51]	Sweet potato transplanting	Two-degree-of-freedom sweet potato transplanting robot arm	A two-degree-of-freedom sweet potato transplanting robot arm was designed with an optimized robot arm control algorithm to reduce the transplanting speed of sweet potato to 1.5 s per seedling.
[52]	Manipulating the spectrum to induce desirable plant characteristics	Light Emitting Diode (LED)	The addition of far-red (FR) Continuous Light CL variable intensity to the RB mix light can stimulate morphological responses and promote better crop growth without interfering with normal plant growth.
[53]	Vegetable transplanter	3-DOF serial obtainable transplanter robot arm, automatic feeding conveyor	The robot is capable of transplanting up to 20 seedlings per minute, with an effective cycle time ranging from 2.5 to 3.1 seconds per treatment.
[54]	Pest removal, targeted spraying	unmanned aerial vehicles (UAVs), infrared thermal imager, sprayer	Drones are very effective in spraying pesticides for various crops as compared to traditional hand sprayers.
[55]	Seed and fertilizer microdosing	Seeding modules, micro-metric fertilizer application modules	Development of a robot for seeding and microdose precision fertilizer application.
[46]	Harvesting pepper fruits	Moving platforms, lifting platforms, end-effector	The improved sweet pepper fruit harvesting robot harvested 61 per cent of the ripe fruits, and the average cycle time to harvest a fruit was 24 seconds.
[56]	Harvest Oyster Mushroom in Greenhouse	Flexible Soft Gripper Manipulator	Oyster Mushroom harvesting robot is proposed, which combines an Oyster Mushroom detection algorithm with the use of a flexible soft claw manipulator to grasp Oyster Mushrooms, with a harvesting success rate of 86.8%, and a single Oyster Mushroom collection time of 8.85 s.

products [31]. Leaf color, spots, degeneration, wilting, *etc*. will indicate the health status of the crops [32]. The height of the crops, the thickness of the stems, the number and size of leaves, and the number and size of flowers and fruits will indicate the growth status of the crops and yield prediction [33, 34]. To meet the diverse monitoring needs, researchers around the world have designed a variety of advanced agricultural robots to perform the tasks, and more representative studies are shown in Table 4.

2. Robots performing agricultural operations

In the whole automation process of vertical farms, as shown, when a large amount of environmental information and crop data are fed into the crop lifecycle decision-making model, a series of agricultural operations will be generated according to the needs of the crops, which need to be performed by agricultural robots. For example, researchers like Arad and Mahmud have developed a pepper fruit harvesting robot [46, 47]. When a small number of pests and diseases are detected in crops, then robots are needed to spray pesticide operations on the corresponding crop areas [48]. If crop nutrition is

Table 6. Scalable agricultural robot for vertical farming.

Reference	Method	Result description
[60]	Modular end effector	Seedling handling and transplanting as well as harvesting in vertical farms by means of modular end-effector, which can be changed according to task requirements
[61]	Scalable multi-module design	The motion of each axis of the robot can be regulated by the size of the plant or the number of seeds, together with the temperature, humidity, brightness, soil sensors, thermal matrix sensor, HQ camera of 12.3 MPx in the module. This data together with the end-effector can collect the agricultural parameters required for the germination of the seeds and intervene in the germination process.
[62]	Reconfigurable manipulator with modular layout	A design strategy for a modular reconfigurable robotic arm for vertical agriculture assisted operations is proposed, allowing the robot to fulfil the different tasks arising from the entire automation process of vertical agriculture.
[63]	Different end-effectors can be fitted	A novel hyper-redundant vertical agricultural robot is proposed with a very high degree of freedom, which can be paired with different end-effector to perform a variety of agricultural activities in spatially crowded vertical farms.

detected to be substandard, robots are needed to light induce growth on the corresponding regional agricultural products to promote the healthy growth of the crops [49]. If the crops are detected to be matured, then harvesting robots need to be arranged to go and harvest the crops [50]. In these areas, researchers around the world have also done a lot of research, as shown in Table 5.

3. Universal agricultural robots

Scale vertical farms will cover a large area, not only will plant a certain type of crops, but a variety of crops with planting [57]. Therefore, in the vertical farm, due to different crops will produce a large number of different requirements of agricultural tasks, if the robot only has a single attribute or only adapted to a single crop, the robot's efficiency will be greatly reduced, the vertical farm equipment costs surge. Therefore, universal agricultural robots, that is, robots that can adapt themselves to agricultural tasks depending on the crop and the agricultural task [58, 59]. Such universal agricultural robots are also being studied by many researchers (Table 6).

Discussion

Benefits for agriculture

As the global population continues to grow, the per capita area of arable land is declining, urbanization is increasing, and the urban population is accumulating on a large scale. The development of vertical farms, which have many advantages, such as efficient use of space to increase the cultivation area of agricultural products [64], greatly shorten the transport chain of agricultural products and satisfy the supply of agricultural products in the region, reduce the consumption of freshwater resources and water pollution, reduce carbon emissions, reduce the use of pesticides and improve the safety of agricultural products, has a great potential for development [65]. To achieve a high degree of automation of the entire vertical farm, a large number of different types of agricultural robots involved in the detection and monitoring of the various crop life cycle, will be obtained by the basic data of the crop input to the crop growth model, or crop digital twin model, to derive the specific operation of the crop [66-68]. And then send the corresponding agricultural robots to carry out the desired operation, and ultimately wait until the crop is mature and then send the crop harvesting robots are then dispatched to perform the operation. Throughout the crop cycle, the vertical farm operates 24 hours a day to improve the optimal growing environment and nutrients required for crop growth, and to obtain agricultural products with higher nutritional value, better shape, and better taste. This prevents the supply chain from being disrupted by a possible future supply crisis or a global flu outbreak [69]. However, there are still many challenges and limitations of vertical farm systems.

Challenges

From this review, it can be found that the development of vertical farming has not yet formed a scale, and the vertical farms constructed in various countries at present are more of a technical verification and are more inclined to experimental nature rather than commercial operation [70]. In a highly automated system such as vertical farms, a large number of various types of agricultural robots are required from the detection and monitoring of various key values in the life cycle of crops, as well as the execution of various agricultural operations encountered in the growth process of crops, but it can be seen that the robots developed for the automation system of vertical farms are still in the minority, and most of the development of agricultural robots is also not targeting a specific agricultural environment, but more of an exploration of the technology [19]. In vertical farms, to seek green development, reduce environmental pollution and reduce the use of pesticides, it is not only necessary to maintain a good environment in vertical farms to reduce the opportunities for pests or weeds to grow, but also need to develop the use of biological control methods. Research on biological control in enclosed vertical farms is still in its infancy [71]. In vertical farms, a large amount of data on crops is obtained from stationary environmental sensors and mobile crop growth detection robots, which must be input into crop growth models to know whether the crops are growing normally or not, and whether the agricultural robots need to perform specific operations to help the crops grow normally [65, 72]. However, research on crop growth models, or even further research on crop digital twins, is still in the developmental stage and the research on these models is also crucial for the development of vertical farms [72, 73].

Conclusion

Regarding the research on the first question, this review found that through the review of the latest agricultural robots applicable to vertical farms, the agricultural robots are currently being developed in all aspects of the agricultural field, but there are still only a small number of agricultural robots developed for the needs of vertical farms, and there are also a lot of robots developed for indoor farms or greenhouses, and small robots or robotic arms developed for outdoor farms, which all There are also many robots developed for indoor farms or greenhouses, and small robots or robotic arms developed for outdoor farms, all of which can be applied to vertical farms with a slight modification of the mobile platform on the premise that the main execution parts remain the same. In response to the second question, the degree of automation in the vertical farms that have been built so far is not very high, and many aspects, such as extensive data monitoring of crops and harvesting, are heavily manual. One of the major obstacles to the development of vertical farms is the economic benefits, and to enhance the economic benefits, the introduction of a large number of agricultural robots, so that the vertical farms are similar to intelligent unmanned factories, which can significantly enhance the economic benefits, so that the study of robotics for vertical farms has great prospects for development [70]. Regarding the third issue, when reviewing the robots applicable to vertical farms, it is obvious that there is not a lot of research on the development of mobile robots applicable to the special environment of vertical farms, as well as relying on various types of detection or monitoring robots in vertical farms to collect environmental data and plant growth data in vertical farms, the research of growth models for crops, and the development of agricultural digital twins have great potential for development. Twin developments are promising.

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