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Review

Technological Trends and Engineering Issues on Vertical Farms: A Review

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Abstract: Vertical farming has emerged as a promising solution to cope with increasing food demand, urbanization pressure, and limited resources and to ensure sustainable year-round urban agriculture. The aim of this review was to investigate the evolving technological landscape and engineering considerations, with a focus on innovative developments and future prospects. This paper presents technological trends in vertical farming, covering advances in sensing technologies, monitoring and control systems, and unmanned systems. It also highlights the growing role of artificial intelligence (AI) in contributing to data-driven decision-making and the optimization of vertical farms. A global perspective on vertical farming is presented, including the current status and advanced technological trends across regions like Asia, the USA, and Europe. Innovative concepts and upcoming enterprises that could shape the future of vertical agriculture are explored. Additionally, the challenges and future prospects of vertical farming are also addressed, focusing on crop production limitations, environmental sustainability, economic feasibility, and contributions to global food security. This review provides guidance on the state of vertical farming, technological advancements, global trends, challenges, and prospects, offering insights into the roles of researchers, practitioners, and policymakers in advancing sustainable vertical agriculture and food security.

Keywords: vertical farm; sensing technology; IoT; automated farm; robot farm

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1. Introduction

The global population is expected to reach 9.7 billion by 2050 and 10.4 billion by 2100 [1], accompanied by a significant urban shift, with 70% of people living in urban environments [2,3]. Rapid population growth and urbanization are exerting immense pressure on food-production systems [4]. As a result, the demand for higher agricultural yields is increasing. Moreover, the expansion of urban areas and the development of infrastructure are further encroaching on farmland, creating food shortages [5]. Addressing these challenges requires innovative approaches, as traditional farming methods have limitations concerning available land and yield.

The increasing global demand for food production, combined with the difficulties presented by climate change and limited arable land, has prompted a critical need for innovative and efficient agricultural practices. Farmland abandonment is a global issue stemming from inefficient agricultural practices, an aging rural labor force, and various other factors. Arable land is left unused due to these challenges. Enhancing farming efficiency and reducing costs through innovative practices is crucial, even in traditional rural areas, to address this trend. To address this issue, the implementation of advanced, precise techniques for food production using controlled environment agriculture (CEA) has garnered increasing attention [6,7]. CEA includes a range of innovative systems like greenhouses, plant factories, and vertical farms, which offer promising solutions to securing sustainable food supplies. CEA systems are designed to protect crops from external weather conditions, thereby reducing their vulnerability to extreme weather events and climate fluctuations. These controlled environments enable precise control, monitoring, and regulation of the microclimate within cultivation areas. This results in higher yields that remain stable throughout the year, supporting year-round production [7–9]. The CEA approach, commonly implemented through advanced vertical farming systems, is progressively recognized as a sustainable method for high-intensity food production, achieved through the use of soilless substrates, artificial LED lighting, and precise control of growth parameters.

Vertical farming, a revolutionary agricultural approach involving multiple levels of crop-growing platforms, is gaining attention for its potential to increase crop yield per unit area of land [5,10]. The profitability of vertical farming may be impacted by rising costs. It is essential to take into account the overall economic viability, considering the increase in various expenses. This innovative crop-cultivation system offers a promising solution to address the challenges posed by population growth, limited arable land, and environmental constraints on traditional farming methods. Urbanization and population growth drive the global vertical farming market, which reached USD 5.6 billion in 2022 and is predicted to surpass USD 35 billion by 2032 (Figure 1). Vertical farming optimizes space, reducing the need for land and construction in cities, with a growing demand fueled by the popularity of organic food [11]. However, vertical farming encounters challenges in sensor technology, innovative cultivation techniques for diverse crops, energy optimization, and automation. These challenges are expected to drive advancements toward more efficient production systems.

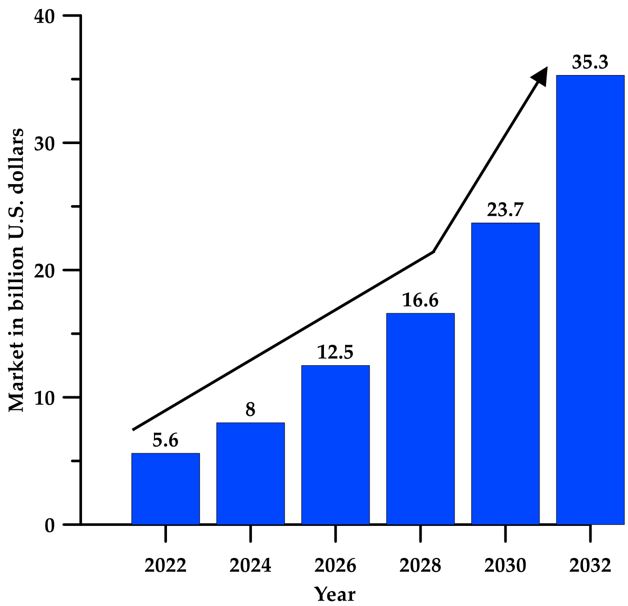

Figure 1. Projected vertical farming market worldwide from 2022 to 2032 (in billion USD) [11].

At the core of vertical farming is the utilization of cutting-edge technological equipment and sophisticated sensors, which facilitate comprehensive monitoring of the cultivation environment. By utilizing automation and actuators, these systems maintain the uniform and optimal conditions essential for crop health and development, leading to improved energy management and resource efficiency [12,13]. Integrating these advanced technologies not only enhances crop yields but also minimizes resource waste, making vertical farming an environmentally sustainable alternative to conventional farming practices [14]. However, integrating sensors and control mechanisms for efficient monitoring and regulation across different levels can be challenging, as it requires sophisticated automation and data-management systems.

Vertical farming technology is experiencing rapid and diverse advancements. The initial phase of indoor farming was primarily concentrated on monitoring and controlling factors such as lighting, nutrients, temperature, and humidity. However, recent developments have led growers to adopt novel technologies for data collection and analysis, aimed at optimizing crop yield [15]. This trend is particularly promising for enhancing food sustainability in urban areas and presents opportunities to positively impact the environment, society, and economy [16,17]. Although vertical farms have demonstrated their potential for producing a wide array of crops, further research is essential in order to achieve technical and economic optimization.

One crucial aspect of this transformation from traditional farming to vertical farming is the changing perceptions of land use [18]. Vertical farming enables the cultivation of crops in urban settings by converting underutilized spaces, such as warehouses, abandoned buildings, or even skyscrapers, into productive agricultural hubs [16]. This reclamation of urban space has the potential to relieve pressure on rural areas by minimizing the need for extensive agricultural lands and preserving natural ecosystems. Moreover, vertical farming systems are highly adaptable and can be tailored to the specific needs of each community, promoting localized and resilient food production.

Numerous studies have been conducted on vertical farming, covering a range of topics, including the various categories of vertical farms [5], prototypes and operational characteristics [16], environmental control and resource efficiency [13,19], smart indoor farm architecture, sensing technologies [4,14], consumer perceptions and acceptance [7,20], and the potential and limitations [6]. However, there is a noticeable scarcity of research focused on advanced technologies, trends, and challenges in vertical farming from the engineering perspective.

Therefore, this review aims to explore the latest technological advancements in vertical farming, including sensors, automation, robots, and artificial intelligence (AI), and discuss how these technologies are integrated into vertical farming systems to enhance crop yield, resource efficiency, and overall sustainability. First, the core aspects of vertical farming are outlined, addressing its concept, classification, and key considerations. Next, it explores current technological trends, highlighting advancements in sensing technology, unmanned vertical farming systems, and AI-based research trends. Then, a global landscape of vertical farming is presented, analyzing industry and market trends in Asia, the United States, and Europe, along with innovative concepts in upcoming vertical farms. Finally, the article investigates the growing need for and promotion of vertical farms, focusing on their potential to address issues related to urban population growth, limited crop diversity, food security, and economic challenges.

2. Vertical Farming: Concept, Classification, and Key Considerations

2.1. Definition and Types

Vertical farms comprise multistory structures designed for the cultivation of fruits, vegetables, and nonedible plants using advanced technologies, similar to high-tech greenhouses and harnessing technologies, and fall under CEA [21]. They are a modern approach to agriculture [20] that addresses challenges in food production due to population growth, environmental concerns, and limited space [15], enabling efficient cultivation of various products in controlled environments for increased yield [22,23].

The term "vertical farming" is difficult to grasp, due to inconsistent definitions given by different publications, industries, and stakeholders and a lack of standardized documentation [24]. In 2010, Despommier [25] introduced the concept of vertical farming to address pressing global challenges with regard to agriculture, food supply, the environment, society, and resource scarcity in the face of population growth and climate change. This idea has engaged scientists, engineers, policymakers, and architects, leading to the establishment of numerous vertical farms globally [26]. During the same year, Japan introduced its inaugural vertical farming facility, which diverged from the conventional commercial enterprise model. Instead, it became an experimental agricultural enterprise affiliated with Chiba University, oriented toward rigorous scientific exploration and investigation [27].

Several authors have introduced the concept of vertical farming, often with varied perspectives. Some of these authors proposed that vertical farming can be considered a "model" or an "initiative", involving the cultivation of crops within high-rise, multistory structures [20,24,28–31].

Vertical agriculture, a term often used to describe vertical farming, intersects with the more sophisticated concept of CEA. However, CEA is not necessarily interchangeable with vertical farming [21,32]. Other indoor-farming concepts, such as high-density vertical growing (HDVG) [15,33], which falls under CEA, and the widely recognized plant factories (PFs), including plant factories with artificial lighting (PFALs) [26] and plant production systems with artificial lighting (PPALs) [34], are part of the concept of vertical farming but are not synonymous with it. Building-integrated agriculture (BIA) and CEA also overlap, forming building-integrated controlled-environment farms (BICEFs) [32]. A less common term, sky farming, pertains to agriculture in high-rise buildings [15]. Waldron [24] provided an overview of these vertical farming concepts, describing their relationships and considering size, density, control mechanism, arrangement, architectural design, and site selection as factors in classifying indoor farming (Figure 2).

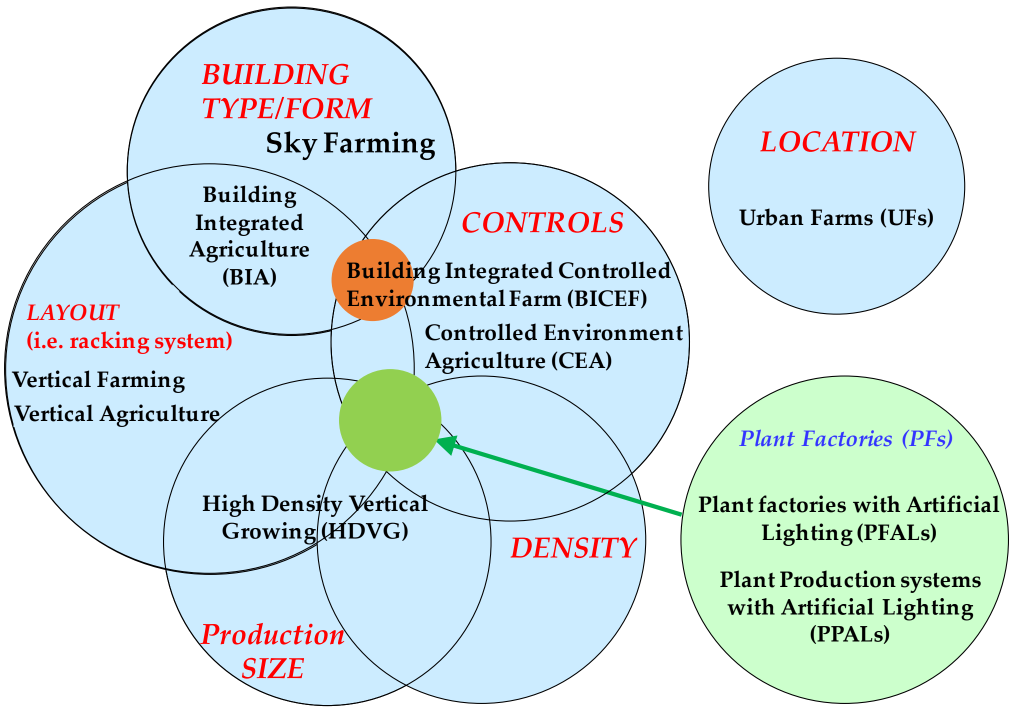

Figure 2. Types of vertical farms and influencing factors (adapted from [24]).

To navigate the complexities of vertical farming, standardization efforts are essential. Developing a unified definition and distinguishing it from related concepts like CEA, HDVG, and plant factories will enhance communication and understanding. Research should focus on refining and optimizing advanced technologies to enhance scalability, resource efficiency, and cost-effectiveness in vertical farming operations.

2.2. General Structures and Characteristics

Vertical farming employs indoor cultivation with stacked layers and artificial lighting (AL) to maximize growing space, ranging from small mobile setups to high-rise structures [35]. It involves creating controlled environments for plants by regulating factors like light, temperature, humidity, CO_2, water, and nutrients, resulting in consistent, high-quality produce regardless of outdoor conditions. These factors can be fully automated by integrating sensors, imaging technology, and artificial intelligence (AI) [36].

Vertical farming encompasses categories like PFALs, container farms, in-store farms, and appliance farms [13,35]. PFALs are purpose-built structures using innovative designs and dedicated buildings tailored for large-scale vertical farming. These types of farms are typically located within industrial spaces and create a controlled environment suitable for industrial-level vertical farming. Modified shipping containers are furnished with vertically stacked racks, LED lighting, and digitally supervised control systems. Using containers for these self-contained vertical farming units ensures adaptability and mobility, allowing easy relocation and space optimization.

In-store farms comprise compact cabinet systems strategically placed in locations where direct consumption or purchases occur, like restaurants, bars, or supermarkets. These vertical farming units are situated at the point of sale or consumption, bringing fresh produce closer to consumers. Appliance farms are designed with a focus on smaller-scale utility and are intended for installation in homes or offices. These plug-and-play indoor-cultivation systems offer the ease and convenience of personalized or limited-scale growing. Additional categories of vertical farming include adaptive reusable buildings, deep farms, balconies, and rooftops [13,23,37,38]. Beacham et al. [5] categorized vertical farming systems, differentiating between stacked horizontal systems and vertical growth surfaces. Stacked horizontal systems include several tiers of horizontally arranged growing surfaces in structures within glasshouses or controlled environments, often incorporating elements like level rotation, multiflora towers, and balconies, whereas vertical growing platforms comprise green walls and cylindrical growth units. In this review, we explored multitiered indoor crop-production systems employing artificial lights in which plant-growth conditions are precisely controlled, which are considered vertical farms.

Figure 3 illustrates the structural elements of a vertical farm. It consists of key components working in harmony to optimize plant growth: (1) a well-insulated and airtight structure resembling a warehouse with opaque walls, creating an ideal plant-cultivation environment; (2) a multitier plant-cultivation bed system equipped with lighting devices positioned above the beds, resembling natural sunlight, to boost photosynthesis and growth; (3) an air-conditioning unit for cooling and dehumidification, complemented by fans to ensure uniform air distribution for healthy photosynthesis and transpiration; (4) a CO_2 delivery system to maintain an optimal concentration for improved plant photosynthesis; (5) a nutrient-solution supply system to ensure that plants receive essential nutrients for growth; and (6) an environmental management system to regulate light, temperature, humidity, CO_2, and airflow, while also managing nutrient-solution parameters [13,23,39]. Water efficiency is vital in vertical farms, where lighting and watering heavily influence overall efficiency. While vertical farms are more water-efficient than modern sensor-controlled farms, both systems necessitate careful water management. As vertical farms are enclosed systems, ensuring secure crop production, lower CO_2 emissions, and efficient resource utilization, they require stringent hygiene protocols. Moreover, advanced technological capabilities should be integrated to effectively monitor and maintain the targeted environmental conditions with precision.

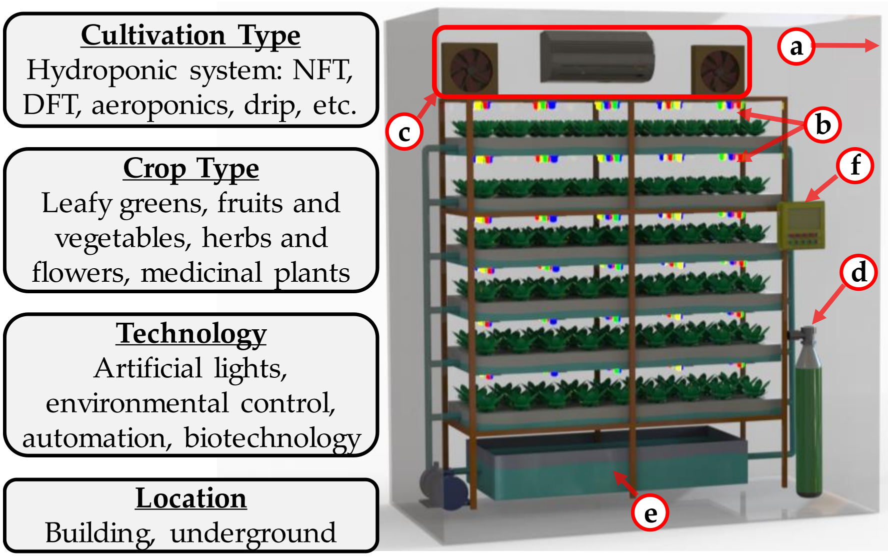

Figure 3. Configuration of a vertical farm: (**a**) thermally well-insulated and tightly sealed walls; (**b**) multilevel structure with lighting equipment; (**c**) air conditioner with fan; (**d**) CO_2 supply unit; (**e**) hydroponic system (nutrient-solution supply unit); and (**f**) environmental control unit. (adapted from [23,40,41]).

2.3. Key Considerations

A vertical farm utilizes advanced technology to efficiently cultivate abundant quantities of food crops and medicinal plants within a confined space. Vertical farming revolutionizes food production by enabling the cultivation of crops within a controlled environment facilitated by artificial lighting. This innovative method is intended to optimize crop yield within restricted spaces, operating independently of fluctuating weather conditions. The establishment and operation of an indoor vertical farm hinge on four key factors, the chosen cultivation approach, the selection of crops, the integration of cutting-edge technology, and the strategic choice of location [41].

2.3.1. Crop-Cultivation System

Vertical farming employs a soil-free methodology (hydroponics) to deliver water and essential nutrients to plants. This technique involves the circulation of a nutrient solution, which operates in a closed loop, and ensures its return to a central reservoir for effective recycling and subsequent reuse. The selection of a vertical farming cultivation technique is frequently influenced by the grower's expertise and technological preparedness.

Hydroponic systems grow plants without soil, providing water and nutrients directly. Although there are multiple approaches to designing hydroponic systems, commercially, methods like the nutrient-film technique (NFT), deep water culture (DWC), and aeroponics are used for recirculating nutrient solutions. In DWC, the recirculating nutrient solution is delivered to plants based on the water level, ensuring that bare roots on a gently sloped bed receive constant nourishment. The NFT and the modified deep flow technique (DFT), which are akin to ebb and flow, are popular on vertical farms [42]. Hydroponics significantly minimizes water evaporation and conserves water, though system disruptions can impact outcomes, even with automated watering. The expenses for nutrients and electricity exceed those for soil-based methods, and nutrient solutions are tailored to specific vegetable requirements. Schematic diagrams with the basic components of each hydroponic technique are shown in Figure 4.

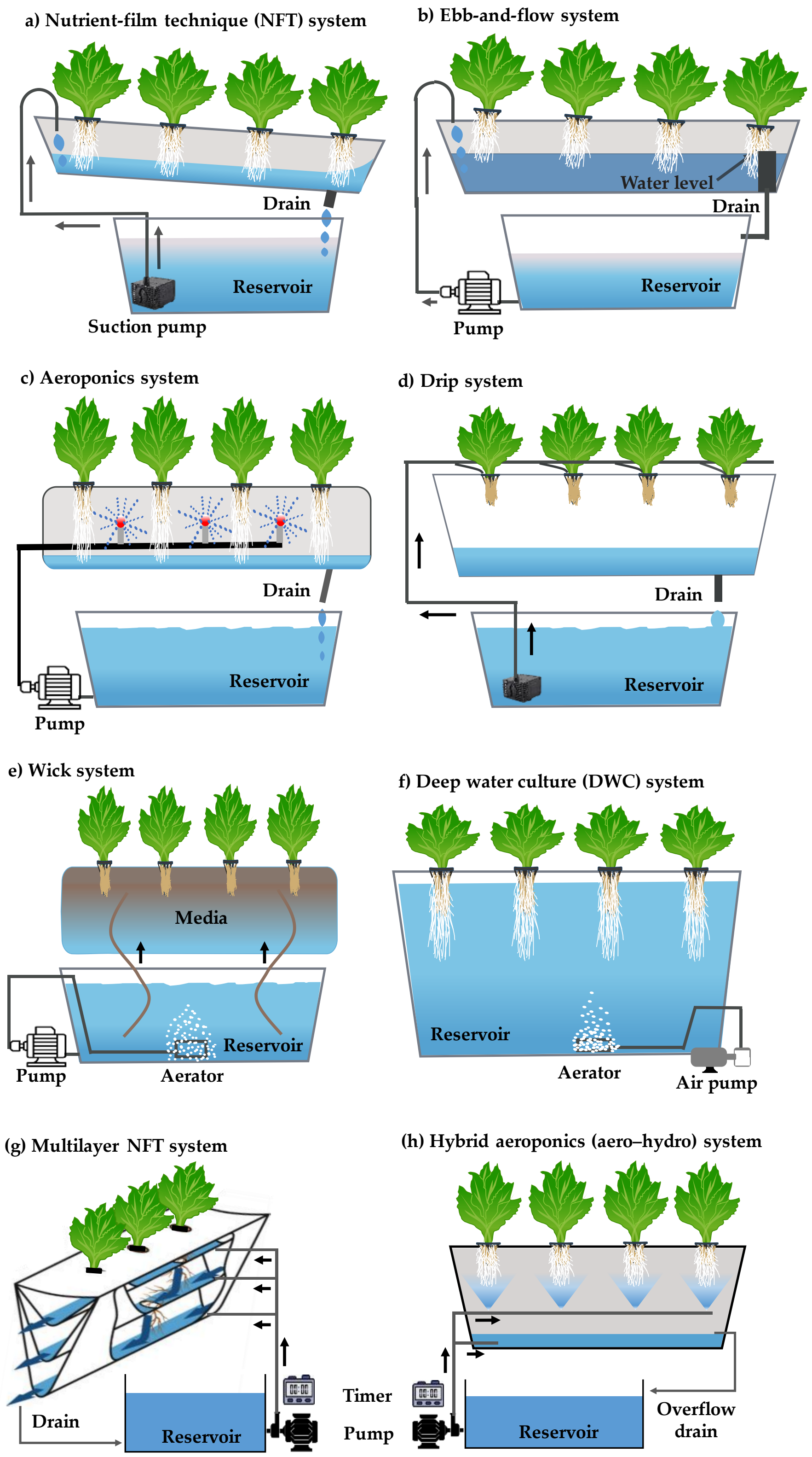

Figure 4. Schematic diagrams of hydroponic systems: (**a**) nutrient-film technique (NFT); (**b**) ebb-and-flow technique; (**c**) aeroponics; (**d**) drip; (**e**) wick; (**f**) deep water culture (DWC); (**g**) multilayer NFT; (**h**) hybrid aeroponics (aero–hydro). Adapted from [42–45].

Aeroponics, a variation of hydroponics, involves misting plant roots with air or a water solution regularly [18], and the plants are typically suspended using boards or foam. This method promotes faster plant growth, requiring precise sensing technology and dosing for optimal results. While aeroponic systems employing air-assisted and centrifugal atomization nozzles have higher initial costs compared to systems using ultrasonic foggers, they potentially have long-term advantages by reducing labor, fertilizer, and pesticide inputs, leading to significantly higher plant yields. To ensure efficient, trouble-free, and cost-effective operation over the long term, routine maintenance and protection from extreme weather conditions are essential for aeroponics systems. These systems are sensitive to climatic conditions in the growth chamber, making weather protection crucial [46].

Hydroponic crop-cultivation methods can be categorized based on several aspects, including the choice of cultivation medium (liquid or culture medium), water circulation (open cycle or closed loop), and aeration method (separate air and water or mixed air and water). To select the most suitable hydroponic technique, it is crucial to understand the unique features of each and compare them with others. For instance, wick and water culture systems are simple to set up and are well suited for home growers. However, if growers aim to cultivate a diverse range or large quantity of plants, NFT, aeroponics, or drip systems are more suitable options. A brief assessment of hydroponic techniques is given in Table 1.

Table 1. Comparison of six commonly used hydroponics techniques.

Considered Parameters	**Hydroponics Techniques**					
	NFT	**DWC**	**Ebb–Flow**	**Aeroponics**	**Drip**	**Wick**
Suitability for vertical farming	High	High	High	High	Low	Low
Nutrient use efficiency	High	Low	Low	High	Low	Low
Aeration requirement	Low	High	Low	Low	Low	Low
Salt build-up possibility	Low	High	Low	Low	High	High
Root-rot possibility	Low	High	Low	Low	High	High
Water saving	High	Low	Low	High	High	High
Long growing period	Low	Low	Low	Low	High	Low
Energy use	Low	Low	Low	High	Low	Low
Pump-failure sensitivity	High	Low	High	High	Low	Low
Setup cost	High	Low	Low	High	High	Low
Maintenance complexity	Low	Low	Low	High	Low	Low

From this comparison, it is evident that each hydroponic technique has distinct strengths and weaknesses relative to the others. Commercial vertical farms, such as Aerofarms, Plenty, and Bowery, primarily use NFT and aeroponics systems in their operations [47–49]. Aeroponics, in particular, offers several advantages over the NFT system. One notable benefit is that it utilizes air as the growth medium, facilitating efficient oxygen uptake by exposed roots. This eliminates the risk of algae growth and the need for chemicals or pesticides [46,50,51]. Furthermore, the nutrient-solution spray not only provides nourishment but also acts as a sterilizing agent, safeguarding the roots against diseases. Additionally, aeroponics maximizes the coverage of the root surface area, surpassing other hydroponic methods in this regard [43,45,52,53].

In recent advancements, researchers and manufacturers have introduced modified or hybrid versions of the NFT and aeroponic systems. A multilayer NFT system has been developed, comprising interconnected layers of circuits at different levels, resulting in small cascades [54]. These cascades enhance the oxygenation of the nutrient solution, which is beneficial for plant growth. The three-layer version of this multilayer trough is specifically designed for leafy crops like lettuce, spinach, chard, celery, cabbage, and aromatic plants. In contrast, the four-layer version is well suited for crops with extensive root systems, such as tomato, pepper, zucchini, eggplant, and cucumber. Additionally, a specialized multilayer dual trough model, featuring a superior and two interior levels, has been developed for the unique requirements of strawberry crops. Eldridge et al. [45] described the hybrid aeroponic (aero–hydro) system, in which the roots mainly develop in an environment of air or fine mist, while a portion of the roots is submerged in a nutrient solution in the plant bed. In the conventional aeroponic setup, any excess nutrient solution not absorbed by the plants is drained from the plant bed. However, in the hybrid approach, a specific quantity of nutrient solution is retained at the bottom of the plant bed, while the remaining irrigation nutrient solution is allowed to drain out.

An advanced cylindrical hydroponics system employing the revoponics technique has been developed [55]. This system enhances plant-growth efficiency by rotating plants around a central light source. The technology offers various configurations, including single, double, stacked, and super-container farming systems, designed for cultivating greens, herbs, and specific types of fruits. An innovative approach known as the binary village design has been introduced, featuring a farming center and a habitat ring constructed from durable concrete. Rapid rotation of plants generates gravitational forces, allowing for zero-gravity plant growth. This design promotes a balanced atmosphere by exchanging oxygen in the farm dome with CO_2 from the habitat ring, benefiting both plant and human wellbeing while being environmentally sensitive [56]. These rotary and cylindrical hydroponics systems support high-density crop cultivation, enabling year-round indoor production of leafy greens. The closed-loop systems enhance water and nutrient efficiency, effectively eliminating runoff. However, further trials are needed to determine which indoor crop varieties are best suited for cylindrical hydroponics to ensure successful vertical crop production.

The Radix hydroponic module [57] utilizes advanced light recipes and hybrid NFT–DWC irrigation modes to enhance crop yield and quality. Featuring four adjustable light-to-bed heights and an independent lighting system utilizing proprietary LED technology, the module offers over 80 optimized light recipes for more than 300 plant varieties. Its adaptable water levels and gravity-driven circulation facilitate the fusion of NFT and DWC. Alkhalidi et al. [58] explored an inventive hybrid of hydroponics and microalgae in a compact two-part shipping container to grow food and produce bioenergy sustainably. A validated mathematical model was used to identify the optimal parameters, including sparger diameter and plant count, for enhanced performance of the integrated system. In another developmental direction, there is an emphasis on plant experience (PX), with a focus on providing diverse vertical farming technologies, including containers as well as nutrient delivery, lighting, and control systems [59]. This approach includes innovations such as hydrobubble technology, in which irrigation water is infused with microsized gas bubbles for improved oxygenation, nutrient absorption, and root health. Additionally, efforts are under way to develop a comprehensive smart system for remote control and management of vertical farms.

2.3.2. Crop Selection

Crop selection in vertical farming should be strategically determined through feasibility studies, taking into account factors like operating costs and demand. Vertical farms prioritize economically feasible crops like leafy greens, herbs, berries, cherry tomatoes, cucumbers, and microgreens, favoring plants that mature quickly and have short height and specific light needs [15,26].

These crops are well suited for vertical farming systems like stacked or cylindrical setups, enabling efficient use of vertical space, higher plant numbers, and increased flexibility for crop rotation and management in response to challenges like diseases or pests. Vertical farming systems can also accommodate other crops like tomatoes and peppers, although their larger size and extended growth cycle pose challenges, and nonedible crops like ornamental flowers can also be considered for production [5]. While commonly used for the cultivation of these crops, vertical farming has the potential for diversification to encompass a wide range of crops. Such expansion could play a pivotal role in advancing sustainable urban agriculture and potentially redefine our approach to food production in the coming years. However, in order to enable the effective cultivation of a diverse range of crops on vertical farms, it is essential to integrate more advanced technologies.

2.3.3. Technological Level

Vertical farming systems have the potential to be implemented in diverse locations. However, costs associated with water supply and temperature-control (cooling or heating) systems can differ significantly depending on the specific environmental context and conditions. The success of indoor vertical farming greatly depends on the efficient use of technology. Technological advancements, including LED lights, sensors, and automation, have revolutionized indoor farming, making it more efficient and tailored to specific crop needs [41].

Lighting plays a critical role in the cultivation of crops on vertical farms, particularly artificial lighting such as LEDs, which replace natural sunlight [10]. Consequently, factors like light intensity and spectral quality have a profound impact on plant growth and development, contributing to enhanced nutritional value and the regulation of essential processes [60,61]. Among artificial lighting options, LEDs have emerged as the most promising choice for horticulture in controlled environments, offering stability, durability, and the ability to cater to specific light spectra [14]. Standard LED technology achieves 28% efficiency, but vertical farming demands higher efficiency, ideally 50–60%, for cost-effectiveness [4,62,63]. However, the capacity of LED-based solid-state lighting is progressing, especially with color-mixing technology [61]. This drives researchers and growers to optimize energy and space by testing various light spectra and crop varieties.

Vertical farming systems offer precise monitoring and control of growth conditions using real-time sensors. Utilizing big data and internet of things (IoT) technology can lead to advanced crop-production knowledge, such as LED lighting and nutrient formulation, through software or firmware applications. Continuous monitoring systems, which measure factors like light, nutrients, and the environment, yield proprietary big data to optimize resource use, reduce cost, and enhance crop quality [14]. Stored in sensor networks, these data aid in developing AI algorithms for optimal growing recipes and efficiency [40]. Automation, coupled with IoT, can minimize costs and human involvement in vertical farming. The cost of this approach offsets the initial expenses by using affordable sensors and reduced labor.

2.3.4. Location

Vertical farming systems ensure consistent year-round production regardless of external factors like sunlight or weather. This versatility allows for production almost anywhere, from harsh tundra to arid desert, extending to densely populated urban zones and even outer space. These adaptable production methods can be implemented in various structures, including repurposed tall buildings, basements, growth chambers, and shipping containers [43].

The choice of location for an indoor farm significantly impacts its infrastructure and operations. In areas where land costs are prohibitive, indoor farms can be strategically placed in neglected spaces like vacant buildings, underground areas, or areas beneath overpasses [41]. Being close to cities reduces the use of fossil fuels by minimizing transportation and human travel, leading to the quicker delivery of fresh produce. Integrating nature into urban spaces promotes access to skilled labor and generates local employment opportunities [16].

3. Technological Trends

3.1. Sensing Technology

3.1.1. Sensors and Actuators

Effective environmental management is essential to maximize plant development in vertical farms. Sensors are critical components that store and analyze environmental data, enabling the optimization of growing conditions [64]. These sensors monitor key parameters like temperature, humidity, light intensity, CO_2 levels, nutrient levels, and pH. These data help in optimizing the growing conditions for plants and improve crop yields.

In advanced vertical farming, sensors and actuators play a role in enhancing automation, efficiency, and ease of management [65]. They reduce the need for constant human intervention by interfacing with environmental variables and capturing critical data, such as light, temperature, and pH changes [4]. Actuators respond to these data by controlling the equipment related to specific parameters, such as ventilation, cooling, refrigeration, pressurization, humidity, and lighting, thus maintaining optimal farming conditions. The synergy between actuators and environmental parameters is vital for precise crop growth with minimal human intervention [66].

Temperature sensors, which utilize thermocouples or resistance temperature detectors, monitor the temperature in real time and convert it into electrical signals. Maintaining humidity is also essential, as it affects plant growth. Accurate moisture conditions and precise temperature control are essential for successful plant growth, as different plant varieties have specific temperature requirements for photosynthesis [67]. The accurate measurement of CO_2 levels is crucial in vertical farming, and devices like nondispersive infrared carbon dioxide sensors (NICDSs) and chemical carbon dioxide sensors (CCDSs) are instrumental in tracking and controlling CO_2 concentrations, which directly impact plant growth and farm productivity [68].

Indoor vertical farms require 8 to 10 h of artificial light per day to support healthy plant growth, with vegetables and flowers having different light demands [69]. Light intensity sensors, such as photoresistors, photodiodes, and phototransistors, ensure that plants receive the appropriate amount of light, considering the varying light demands of different plant types [4]. These sensors provide real-time data on light intensity and specific wavelengths, contributing to ideal light conditions for plant growth. Water-level sensors automate the monitoring of the nutrient-solution reservoirs, providing real-time data for precise monitoring and control. Electrical conductivity (EC) and pH sensors are also valuable in vertical farming for measuring these factors in nutrient solutions. These sensors help to ensure nutrient balance and a suitable pH, facilitating effective nutrient absorption [70]. Integrating a range of sensors, such as those for temperature, light intensity, water level, and EC/pH, provides growers with real-time insights to make informed decisions, which will ultimately enhance crop quality and quantity in vertical farming environments.

Actuators are crucial components of vertical farming, as they enable precise control over various environmental factors. These devices translate electronic signals into mechanical actions, facilitating dynamic adjustments to optimize plant growth. Actuators play an essential role in adjusting lighting positions, regulating airflow, and managing irrigation systems [4,66]. Motorized mechanisms controlled by actuators position artificial lights at optimal distances from plants, ensuring even light distribution. By regulating airflow through ventilation systems, actuators maintain consistent air quality and temperature, vital for healthy plant development. Furthermore, actuators also automate irrigation processes by controlling valves and pumps to deliver precise amounts of water to the plants, minimizing waste and ensuring consistent hydration, thus enhancing water-management efficiency. This automation not only enhances resource efficiency but also reduces labor demands. Incorporating actuators in vertical farming setups increases precision, responsiveness, and resource optimization, leading to enhanced plant growth and overall farm productivity. Table 2 summarizes the fundamental features and applications of key sensors and actuators, highlighting their usability in CEA, including vertical farms.

Table 2. Fundamental features, usability, and applications of most used sensors and actuators in CEA, including vertical farms.

Item	Type	Specification	Applications	Image
Sensors	Temperature and humidity	Measuring range: −40–80 °C, 0–100%; Accuracy: ±2%, ±3%; Response time: 5 s; Resolution: 0.1 °C, 0.01%; Power input: 3.3–5.5 V	• Measures the temperature and humidity of the ambient air; • Optimal temperature and humidity range for leafy greens of 18–24 °C and 50–70%, respectively.	
	CO_2	Measuring range: 0–10,000 ppm; Accuracy: ±5% Response time: 10 s; Resolution: 1 ppm; Power input: 3.3–5.5 V	• Measures the CO_2 in the ambient air with; • Optimal CO_2 range for leafy greens is 800–1500 ppm.	
	Light intensity	Measuring range: 0–3000 W/m^2; Accuracy: ±1% Response time: 10 µs; Sensitivity: 4 µA per 1000 PPFD in water	• Measures the light intensity inside the growth chamber; • Optimal light range for leafy greens is 50–250 PPFD.	
	Electrical conductivity (EC)	Meas. Range: 0–20,000 µS/cm; Accuracy: ±4–8% Response time: 5 s; Resolution: 1 ppm; Power input: 5 V	• Measures total dissolved salts in the nutrient solution; • Optimal EC range for leafy greens is 1.4–1.8 mS/cm.	
	pH	Measuring range: 0–14; Accuracy: ±0.2%; Response time: 1 s Resolution: 1 ppm; Power input: 5 V	• Measures the pH of the nutrient solution; • Optimal pH range for leafy greens is 5.5–6.0.	
	Ion-selective electrode (ISE)	Measuring range: 1–14,000 ppm; Accuracy: ±10% Response time: 1 s; Resolution: 1 ppm; Power input: 5 V	• Measures nitrogen concentration of the nutrient solution; • Optimal nitrate range for leafy greens is 100–150 ppm.	
	Dissolved oxygen (DO)	Measuring range: 0–20 ppm; Accuracy: ±2%; Response time: 40 s; Resolution: 0.006 ppm; Power input: 5 V	• Measures the DO of the nutrient solution; • Optimal DO range for leafy greens is 7–8 ppm.	
	Water level	Measuring range: 0.1–3 m; Accuracy: ±0.2%; Resolution: 0.5 mm Dead band: 0.1 m; Power input: 12–28 V	• Measures the water level of the nutrient blending tank as well as stock-solution tanks.	

Table 2. *Cont.*

Item	Type	Specification	Applications	Image
Actuators	Heater	Power input: 110, 220 V; Power: 2.8 kW	• Used to increase ambient air temperature.	
	Cooler	Power input: 110, 220 V; Lowest temp: 0 °C; Coverage: 450 m^2	• Used to decrease ambient air temperature.	
	Humidifier	Power input: 110, 220 V; Coverage: 2000 m^2; Power: 2.2 kW	• Used to increase ambient air humidity.	
	Dehumidifier	Power input: 110, 220 V; Humidity removal: 2.5 L/h Air flow rate: 30 m^3/h; Coverage: 50–100 m^2	• Used to decrease ambient air humidity.	
	LEDs	Power input: 110, 220 V; Light intensity: 17,400 flux; Output: 300 W	• Used to supply plants with the desired light intensity.	
	Fan	Power input: 110, 220 V; Air flow rate: 4400 m^3/h Output: 1.1 kW, 437 rpm	• Used to circulate the ambient air.	
	CO_2 regulator	Power input: 110, 220 V; Flow rate: 0.5–15 SCFH Control type: Digital, solenoid	• Used to maintain the target CO_2 level inside the growth chamber.	
	Nutrient pump	Power input: 110, 220 V; Maximum flow: 100 L/min Maximum head: 24 m; Power: 0.75 HP/0.55 kW	• Used to supply nutrient solutions to the root zone of plants.	

3.1.2. Nutrient-Sensing Systems

Maintaining optimal nutrient levels in hydroponic systems is crucial, as plants require different amounts of nutrient ions at different growth stages for both physical development and functional maturation [71]. However, allowing an excess of stock solution to enter the nutrient mixing tank can lead to toxicity in the target nutrient solution, while inadequate flow can result in nutrient deficiencies. Both scenarios can impede the sustainable growth and development of plants [72]. Traditionally, farmers rely on visible symptoms in plants to identify nutrient deficiencies or toxicity, which only become apparent after extended periods of inadequate nutrition. Moreover, similar visible symptoms caused by different nutrient deficiencies can often lead to misdiagnosis and incorrect nutrient supplementation [52].

Monitoring nutrient levels in hydroponic solutions by assessing electrical conductivity (EC) and pH levels in real time is a commonly employed approach. Although this method provides instant information about nutrient levels, it has limitations in identifying specific nutrient ions present in the solution. It cannot differentiate between types and quantities of individual ions within the solution [73–76]. Moreover, adjusting the pH level can influence the EC level by triggering precipitation or dissolution reactions. Some farmers regulate the nutrient solutions according to specific ions through offline analysis, which involves sending the nutrient solutions or plant-leaf samples to an established laboratory. However, this approach is inconsistent, and the delays involved in transportation, ion analysis, and reporting result in significant changes in the on-farm nutrient solution, rendering the entire effort futile.

Furthermore, in a closed hydroponic system, accurately determining nutrient concentrations in the recycled solution is vital in order to maintain an optimally balanced nutrient solution [77]. Continued recycling of drainage water may result in the buildup of specific nutrients like calcium, causing changes in nutrient proportions [78]. Considering these challenges, adopting an ion-selective nutrient-sensing technique emerges as a critical solution. This kind of technique addresses the limitations of visual assessment, EC- and pH-based monitoring, and other offline nutrient-assessment methods by providing ion-specific nutrient monitoring, robust real-time sensing capability, a simple calibration process, and easy maintenance. Figure 5 illustrates several hydroponic nutrient-monitoring techniques.

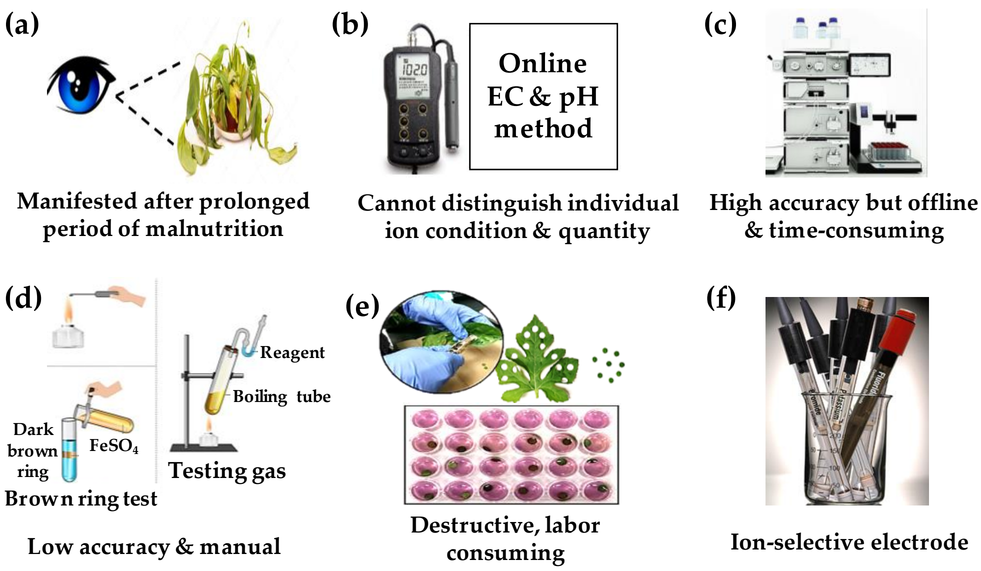

Figure 5. Hydroponic nutrient monitoring techniques include (**a**) visual assessment of plant symptoms; (**b**) electrical conductivity (EC) and pH assessment; (**c**) laboratory analysis using an ion chromatography machine; (**d**) manual salt testing; (**e**) leaf tissue analysis; and (**f**) ion-specific nutrient analysis using ion-selective electrodes.

Recent advancements in analysis techniques, such as multivariate standard addition, coupled with AI tools like artificial neural network (ANN), deep neural network (DNN), and deep kernel learning (DKL) models, along with approaches like the multivariate standard addition method (MSAM) and feature enrichment (FE), have been employed for more precise and accurate determination of multiple ions in hydroponic nutrient solutions [79–83]. Figure 6 illustrates the combination of multivariate standard addition, feature enrichment, and DKL, showcasing their collective utility in quantifying the various ions present in hydroponic nutrient solutions. Additionally, advanced signal-processing algorithms are utilized to mitigate inherent and external errors associated with ion-selective electrodes (ISEs) [84]. Recent research efforts have also focused on developing calibration-free methods [85] and antifouling polymeric membrane ISEs to extend their operational period [86].

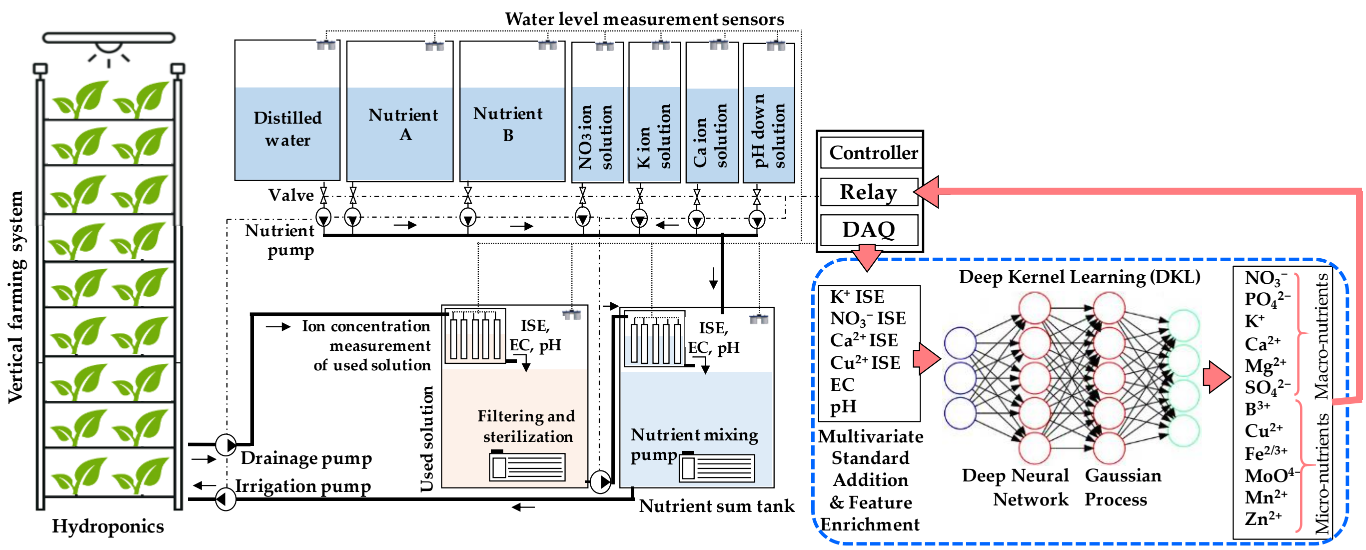

Figure 6. Combined application of several AI-based algorithms (MSAM, FE, DKL DNN, and GP) to determine multiple ions in hydroponic solutions.

Integrating AI in hydroponic crop cultivation offers numerous advantages but also presents challenges and potential drawbacks. The benefits of AI applications include improved crop monitoring, enhanced resource efficiency, optimized yields, early detection of disease or nutritional deficiencies, data-driven decision-making, and reduced labor [87–89]. However, implementing an AI system can be costly, especially for small-scale growers, as it involves expenses related to hardware, software, and training, which may require specialized knowledge or technical expertise to effectively operate the system. Relying heavily on AI for crop management can lead to dependency issues, requiring growers to maintain their knowledge and skills related to traditional methods in case of system failure. Additionally, challenges, such as the lack of standardization in software and hardware, concerns about data security, and increased energy consumption for the operation of sensors and actuators, are potential drawbacks of using AI in vertical farming [90,91]. Growers should carefully assess the advantages and disadvantages in order to select the most suitable AI tools for their hydroponic system.

3.1.3. Plant Monitoring and Control Systems

It is of utmost importance to monitor and control plant conditions in order to optimize crop quality in vertical farming systems. In recent years, IoT technology has gained widespread recognition and adoption in modern agriculture, particularly in vertical farming cultivation and management [68,92]. This cutting-edge approach utilizes IoT-enabled devices to continuously monitor and control the crop-growing environment, enhancing food production with limited resources [93,94]. The integration of IoT-based applications has drawn significant attention due to their capacity for enhanced monitoring and precise control, promoting sustainability in agriculture. These interconnected systems rely on an array of sensors, actuators, and data-analytics tools to facilitate real-time monitoring of crucial environmental factors [95,96]. The platform's advanced applications provide updates to farmers about crop-growing conditions, enabling them to take timely action and make decisions that can help to ensure crop quality and productivity.

Growers can customize the environments for different crops through IoT-enabled devices, confirming standard growth conditions for individual plants remotely [97,98]. This minimizes resource waste, reduces reliance on chemicals, and lessens the ecological impact associated with traditional farming. Challenges like efficient water and nutrient management are achieved through the use of sensors that provide information on water and nutrient levels. This information guides the application of these resources precisely during times of crop demand. Furthermore, IoT platforms can seamlessly integrate real-time meteorological data, enhancing their capability to predict atmospheric conditions and enabling proactive adjustments.

The significance of the IoT extends to pest and disease management through data analysis and modern technology. Because IoT devices are easy to use in the agriculture domain, researchers are motivated to integrate IoT solutions with machine-learning approaches [99–101]. Employing sensors equipped with image-recognition capability allows for the rapid detection of signs indicating infestation or disease. The integration of IoT applications in vertical farming has remarkable potential to revolutionize urban agriculture [4]. By facilitating precision agriculture, conserving water, optimizing energy usage, and enhancing pest-management strategies, IoT-driven vertical farming emerges as a sustainable and transformative solution to the contemporary challenges of food production. A schematic illustration of IoT-based monitoring and control systems designed for vertical farms is shown in Figure 7.

Visual sensor technology revolutionizes vertical farming by enabling comprehensive crop growth monitoring through image-based analysis [43,102,103]. Sensors capture visual data, providing valuable insights into plant health and development. High-resolution cameras continuously monitor plants, leaves, and fruits, offering real-time information on growth patterns, disease symptoms, and stress indicators [104]. These data aid in the early detection of issues and facilitate timely interventions. Visual sensors also automate plant monitoring, using computer-vision algorithms to assess plant density and size, and even fruit ripeness. This streamlines labor-intensive tasks, enhancing operational efficiency [105,106].

Integrating visual sensor technology in vertical farming empowers farmers to make informed decisions, adjust their cultivation practices, and optimize resources. This data-driven approach ensures healthier crop growth, supports sustainable farming practices, and boosts yields [107]. Chlorophyll-fluorescence sensors analyze photosynthetic activity, indicating plant stress levels [108]. Spectral sensors measure light absorption and reflection, aiding in the detection of nutrient deficiency [109]. Optical sensors also contribute to light management, with quantum sensors measuring available light for photosynthesis, enabling farmers to adjust artificial lighting setups [110]. Additionally, multispectral sensors can assess plant health through changes in color and reflectance. These technologies enhance precision and efficiency in vertical farming [111]. Recently, portable optical sensors have been developed to monitor plant stress, offering a valuable tool for early diagnosis and real-time plant health assessment on farms [112]. A portable Raman leaf-clip sensor is becoming essential for diagnosing nitrogen deficiency in plants [113]. These advancements in optical sensor technology improve the precision and efficiency of vertical farming, ultimately leading to enhanced crop yields and sustainability.

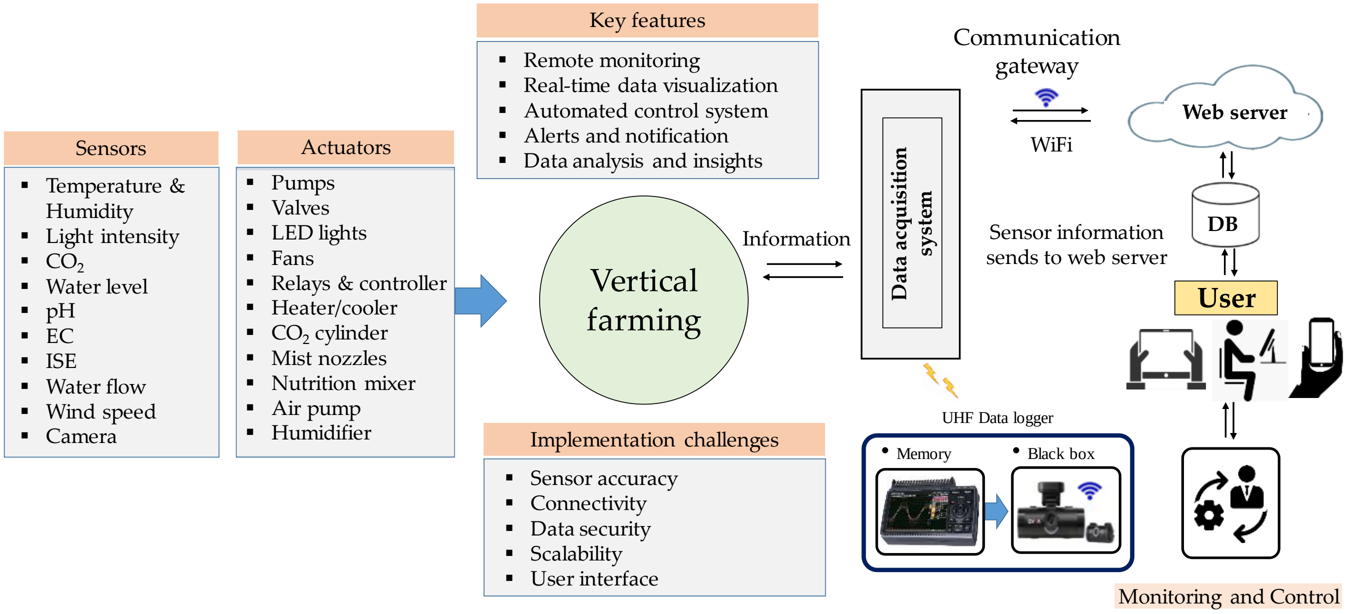

Figure 7. Schematic representation of IoT-based monitoring and control systems for vertical farms.

3.2. Unmanned Vertical Farming Systems

Unmanned vertical farming systems represent a cutting-edge innovation in agriculture by blending technology and innovation to revolutionize crop cultivation [114]. These systems integrate automation, robotics, and advanced sensing technology to create controlled environments in stacked layers, optimizing plant growth. By incorporating real-time data and precise control mechanisms, these systems offer accurate management of environmental variables like light, temperature, humidity, and nutrient delivery, ensuring optimal conditions for plant growth. This precision leads to increased yields and resource efficiency, substantially reducing labor costs [4].

Automated nutrient- and water-delivery systems, coupled with real-time monitoring, enable the efficient use of resources, leading to significant reductions in water consumption and a decreased reliance on external nutrient sources [115]. Unmanned vertical farming systems are not constrained by seasonal changes or adverse weather conditions, enabling year-round crop production, which contributes to food security [4]. Additionally, by minimizing pesticide use and reducing transportation distances, these systems can contribute to lowering carbon emissions and producing a smaller ecological footprint [116]. The integration of sensors and data analytics provides real-time insights into plant health and growth, offering a platform for experimenting with new crop varieties, growth methods, and technologies [114]. Furthermore, vertical stacking maximizes the utilization of available space, making these systems particularly suitable for urban areas with limited available space [14].

Unmanned control systems are increasingly integrated into diverse farming practices, including controlled greenhouses, livestock farming, and aquaculture, to enhance efficiency, reduce labor costs, and enhance overall production. In controlled greenhouses, robotics and conveyors automate tasks, reducing labor costs and incorporating water recycling to promote sustainability. These greenhouses create controlled microclimates within a single structure to meet the needs of diverse crops. While these technological control systems offer numerous farming advantages, it is crucial to address challenges and limitations, including the need for ongoing maintenance, potential technical failures, and the initial investment required.

3.2.1. Automated Vertical Farming Systems

Automation in vertical farming addresses challenges posed by high labor costs, a lack of skills, and the demand for increased efficiency. The reduction of human involvement not only cuts disease risks but also enhances safety and productivity in vertical farming systems [43,117]. Various automation applications play pivotal roles in shaping the future of vertical farming, including seeding, transferring seedlings to vertical beds, automated watering, lighting, fertilization, crop monitoring via visual systems, automated harvesting, and bed cleaning and reloading [118]. These technologies contribute to cost reduction, provide essential data for optimized solutions, and facilitate IoT-connected farming for precise monitoring of and feedback on growth conditions.

The emergence of mini vertical farm systems, suitable for home or small business use, highlights the integration of automation. These systems autonomously manage climate, hydroponics, LED lighting, and growth via apps. However, the reliance on manual harvesting and planting currently limits full automation and potential yield optimization [119]. Conversely, fully automated vertical farming systems cover a range of processes, including sowing, planting, light control, fertilization, harvesting, and cleaning, demonstrating the capability of intelligent software-driven setups [120]. Such systems ensure real-time monitoring, precise planting, and rapid sowing, performing 10–30 times faster than manual methods on a 20-layer vertical farm. However, the cost factor remains a consideration, as this fully automated system is two to three times more expensive than the commonly used semiautomatic system. Table 3 highlights the key technical features of several automated vertical farming facilities.

Table 3. Key technical features of investigated automatic vertical farming facilities.

Vertical Farm	Location	Key Technical Features	Reference
GreenCUBE	Singapore	• Employs uniform steel components for pallet storage and iCube setups; • 2D shuttles and lifts manage all bench shifts; • Software enables various picking approaches, optimizing aisle usage; • Safety zones are configured for enhanced security.	[121]
iFarm	Helsinki, Finland	• Crops are moved from the seed zone to the harvest area automatically; • Monitors and manages farming via the Growtune SaaS platform; • Irrigation with constant EC and pH control and automatic mixing of precise nutrition blends.	[122]
Seasony	Copenhagen, Denmark	• Integrates cutting-edge AI and robotics for efficient farming; • Watney, an autonomous mobile robot, manages vertical farm logistics; • Startup's software controls robots and analyzes data for farming insights.	[123]
Organifarms	Konstanz, Germany	• Applies image recognition and robotics for automated berry picking; • AI-powered robot gently assesses strawberry ripeness and quality; • Enables touchless harvesting for precise filling and cost savings.	[124]
Eagle Technologies	Michigan, USA	• Dispensing tech automates seeding, watering, lighting, and fertilization; • Cutting-edge vision tech tracks plant health and growth; • Advanced robots plant, pick, and palletize crops from beds or planters.	[118]
Intelligent Growth Solutions	Edinburgh, Scotland	• Developed a 3-phase LED technology that adjusts intensity across all wavelengths with 90%+ power efficiency; • Blended AI and ML controls light for 50% more efficient lighting; • Utilizes efficient closed-loop ventilation.	[125]

Table 3. *Cont.*

Vertical Farm	Location	Key Technical Features	Reference
Badia Farms	Dubai, United Arab Emirates	• Computer-linked units control environmental inputs and schedule irrigation and feeding; • Uses up to 90% less water than open-field-grown crops.	[126]
Spread (Techno Farm Keihanna)	Kyoto, Japan	• Among the largest automated vertical farms globally, it employs advanced tech like robotics, IoT, and other leading-edge tech; • Factory data stored in Techno Farm cloud IoT platform, analyzed by AI for best conditions; • Nanolevel filtration reuses most cultivation water, around 90% recycled by collecting plant transpiration.	[127]
A-Plus (Farm and Factory TAMURA)	Fukushima, Japan	• Uses automated farming from sowing to transplanting and harvesting; • Pioneered a monorail transport system for automation; • Utilizes cutting-edge automation tools like robots and solar power generation.	[128]
Itoh Denki	Kasai, Japan	• Uses an underground automated plant factory with modular cells; • Cells feature motorized tray movement and adjustable LED lighting for color, intensity, and distance; • Plants grow underground for 40 days, receiving nutrients and CO_2 automatically.	[129]

SANANBIO [130], a leading global indoor-farming technology provider, has introduced UPLIFT, an unmanned vertical farming system (Figure 8). It focuses on sustainable food production using advanced indoor-farming and horticultural lighting technologies. UPLIFT automates key processes like seeding, transplanting, harvesting, and cleaning through robotics and AI-driven production lines (Figure 8a). The system allows for remote monitoring and management of farm operations. It integrates LED grow lights and nutrient circulation in a 24-layer grow-rack system (Figure 8c,d). Furthermore, PlantKeeper, a wireless control system (Figure 8b), is a production-management system capable of gathering, storing, and analyzing data. This aids farm operators in monitoring and adjusting environmental conditions, lighting schedules, and plant growth.

The challenges of traditional agriculture have driven the rise of high-tech greenhouses and indoor vertical farms. These developments have led to the adoption of smart technologies using sensors, big data, robotics, and AI for efficient cultivation. In vertical farming, automation varies from manual to advanced systems, impacting labor and energy efficiency. The StackGrow technology of iFarm, Helsinki, Finland [122] cuts labor by 30% and energy by 33%. Around 28.4% of vertical farms use IT-driven automation, with more adoption planned [131]. Vertical farms face challenges in profitability due to their higher electricity usage for lighting, while greenhouses demand increased costs for climate regulation and have more land requirements. Vertical farms require heating and cooling systems for precise environmental control, giving them an edge in product quality and consistency over greenhouses.

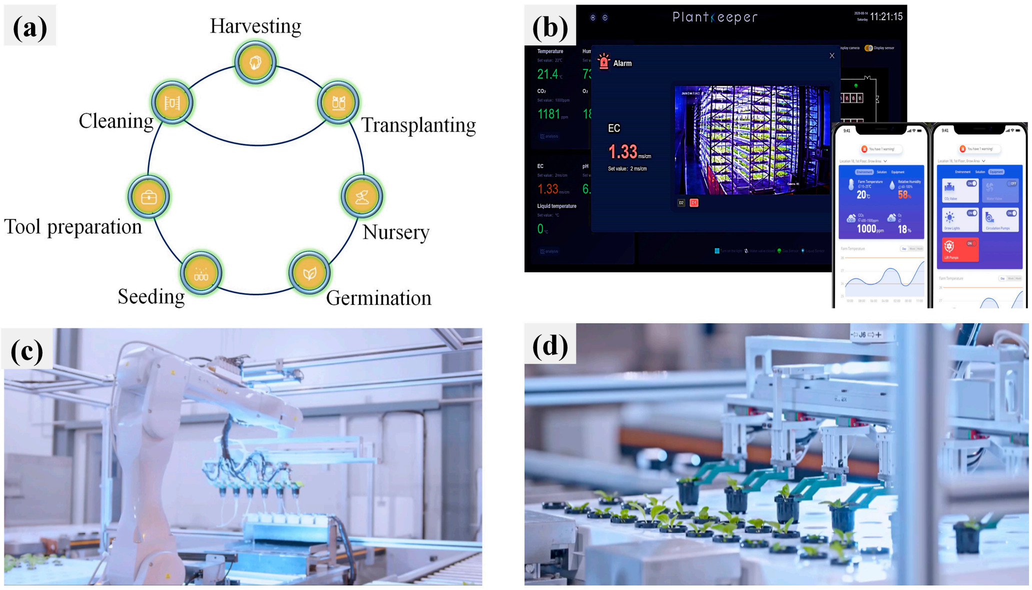

Figure 8. Unmanned operation in vertical farming: (**a**) key processing steps; (**b**) PlantKeeper wireless monitoring and control app menu; and (**c**,**d**) automated production and management. Adapted from [130].

3.2.2. Robotic Vertical Farming Systems

The integration of robotic systems in vertical farming is increasingly essential due to the physical and economic limitations of human labor. The high-density cultivation and physical constraints of vertical structures make human labor impractical and inefficient. Robotic systems are skilled at complex tasks like precise harvesting, maintaining a controlled environment, minimizing human error, and providing the consistency needed for optimal crop yields and quality. Robotic vertical farming systems address the challenges with precision and efficiency, particularly in mitigating the reliance on human labor. As labor costs constitute a significant portion of total expenses (25–30%), robots emerge as efficient, consistent, and precise performers across various tasks, effectively mitigating both fixed and operational costs. Incorporating smart technologies enhances automation and robotics, offering improvements in resource efficiency, productivity, and sustainability in controlled-environment agriculture.

Autonomous robotic platforms equipped with versatile sensors on vertical farms can be crucial in advancing these goals [115], while robotic applications for planting and harvesting are present but not fully effective due to some challenges. Many vertical farming systems still rely on manual labor due to robot limitations in handling diverse crops and complex canopies. Existing robots are slow, damage crops, and struggle with recognition, and their safety alongside humans must be ensured while preserving plant integrity [43].

iFarm [132] is a modular indoor vertical farming system that supports year-round, pesticide-free plant growth through automated climate control, LED lighting, and efficient power management. Its innovative technologies include a chatbot for plant image analysis and a neural network that calculates plant mass dynamics. A fully automated prototype with a conveyor-belt system and robotic packaging (Figure 9a,c) was tested in February 2021. It integrates machine vision with cameras to assess plant health using a trained neural network (Figure 9b). iFarm's Growtune software oversees processes from planting to sales, providing clear instructions and monitoring. Ongoing research helps to improve crop quality and farm efficiency, with growth-recipe updates for farm owners through Growtune.

In recent years, Iron Ox [133] has been refining agricultural robots for indoor farming and launched its fully autonomous production farm after successful small-scale testing. This farm grows various leafy greens like romaine, butterhead, kale, basil, cilantro, and chives. The robots include Angus, a 1000-pound machine (Figure 9d) that moves hydroponic boxes and has a robotic arm for harvesting. IGS [134] has introduced total controlled environment agriculture (TCEA), a cutting-edge platform shaping the future of indoor farming. The system seamlessly integrates various components with proven off-the-shelf technology. Urban Crop Solutions [135] produces different kinds of automated unmanned vertical farming solutions, such as ModuleX (a plant factory), FarmLab (a customizable research system), FarmFlex (a customizable rack setup), and UCS mission control (monitoring and optimizing software).

Figure 9. Unmanned operation in vertical farming: (**a**) automatic conveyor belt (adapted from [133]); (**b**) control video camera on a rack (adapted from [133]); (**c**) 1000-pound robot named Angus (adapted from [136]); and (**d**) Iron Ox's robotic arm for harvesting (adapted from [136]).

Avgoustaki et al. [115] demonstrated how low-altitude multispectral images can be used to spot plant growth and quality, thereby curtailing nutrient and water consumption. This noninvasive visual technique is ideal for autonomous robots on vertical farms. This method could greatly ease the automation of herb and vegetable cultivation on indoor vertical farms, substantially cutting labor-related production expenses. Marchant and Tosunoglu [137] suggested a robot for planting and harvesting on the CityCrop automated indoor farm. A camera that detects ripe crops is mounted on a manipulator that also plants, controlled by a proposed algorithm. A leading Dutch vertical farm, Future Crops, uses data-driven technology and a "plant whisperer" approach [138] to optimize growth conditions. It employs automation, powered partially by 16,000 rooftop solar panels, to regulate factors like humidity, temperature, and light. With 8000 m^2 of potential cultivation space, it is set to become one of Europe's largest and most globally significant vertical farms [35].

Recent advancements in agricultural robotics have addressed some of the challenges in vertical farming. Deep learning enhances a robot's ability to recognize various types of produce, while active sensing assists in navigating complex environments. Specialized robots and grippers are designed for handling delicate crops, and improved human–robot interactions ensure safe collaboration. Simplifying the farming environment by standardizing cultivation panel sizes and crops with robot-friendly traits can further facilitate robotic operations. Although vertical farming partially relies on automation for control, lighting, and irrigation, there is significant potential for integrating with sensor technology, crop models, and AI. While the integration of container-handling robots is possible, ensuring safety around plants and humans requires additional research. Modular structures could also facilitate the expansion of autonomous vertical farming systems [43].

Agricultural technology is evolving to meet the demands for automation, digitization, and sustainability. Trends indicate a shift toward smart farming, with the incorporation of the IoT, AI, drones, and robots for tasks like planting and monitoring. Data collected from sensors and imagery enable precise decision making, while indoor farming and precision agriculture are driving sustainable changes aimed at improving crop yields and fostering a sustainable future [139].

Robotic systems are gaining popularity in agriculture, particularly in vertical farming, promising labor-cost reduction and increased efficiency, but their implementation requires careful consideration. High initial investment and technical expertise pose significant barriers for smaller or resource-constrained vertical farms. Regular maintenance and specialized knowledge contribute to increased costs. Limited adaptability to crop variety and changing conditions requires constant reconfiguration or investment in new robotic equipment. Additionally, factors like larger energy consumption, technology dependence, and the need for human supervision are crucial considerations in vertical farms. Addressing these limitations will be crucial as technology continues to evolve for the full realization of the potential of robotic systems in vertical farming.

3.2.3. Vertical Farming with Drones

The convergence of vertical farming and drone technology marks a new era of agricultural innovation, redefining the possibilities for crop cultivation in controlled environments. In the face of global challenges in food security, resource scarcity, and environmental sustainability, the fusion of these two cutting-edge fields offers immense potential to revolutionize how we grow and manage crops. The space-efficient and climate-controlled setups of vertical farming complement the capabilities of drones, which provide aerial precision and data-driven insights. This transformative synergy addresses critical agricultural challenges while opening new frontiers in sustainable food production.

Since 2020, AeroFarms [47] and Nokia Bell Labs [140] have collaborated to explore and refine concepts, conducting tests with commercial crops. Nokia Bell Labs provides expertise in autonomous drone control, private wireless networks, advanced imaging, sensor data pipelines, and AI technology for mobile sensors. Drones autonomously fly over vertical farm crops, capturing images of each plant and collecting data on various plant health indicators such as leaf size, stem length, coloration, curvature, spotting, and tearing. The entire system is adaptable and resilient, and it uses a 5G private mobile network and cloud-based processing technology to ensure minimal delay and robust data security within an on-site network [141].

iFarm [132] is effectively experimenting with computer vision technology to enable the monitoring of plant-growth stages on vertical farms using UAVs (Figure 10). Their research focuses on methods to assess plant weight through images and determine optimal lighting modes based on power consumption and leaf-growth speed. They are also exploring the use of autonomous drones to enhance data-collection speed and improve the capabilities of the neural network [142]. Corvus Drones [143] has introduced an innovative autonomous drone tailored for horticulture, specifically designed for tasks like seed germination and flower detection. Growers can easily program flight routes via a web app, assign tasks to drones, and enjoy autonomous execution, including recharging without human intervention. This technology offers rapid reporting, cost savings, improved labor planning, and reduced crop risks. Arugga [144] provides robotic solutions for tomato greenhouses and vertical farms, featuring a mobile ground robot named Polly. Polly autonomously navigates between rows of plants and uses air pulses to facilitate pollination. Robotic pollinators in vertical farming could bring several advantages, including a reduced risk of plant infections often associated with bee-mediated pollination. They also contribute to the preservation of wild bee populations, which are declining due to factors such as climate change, urbanization, and pesticide use, which will ultimately benefit outdoor pollinator-dependent plants [145].

Figure 10. Use of UAVs in vertical farming: (**a**,**b**) autonomous drone (iFarm, Abu Dhabi, UAE) (adapted from [132]); (**c**) autonomous drone (adapted from [132]); and (**d**) AI drones (adapted from [140]).

The fusion of vertical farming and drone technology holds remarkable promise, offering precision, efficiency, and sustainability. By harnessing the aerial capabilities of drones within the controlled environment of vertical farms, we have the potential to revolutionize food production.

3.3. AI-Based Research Trends

AI is an efficient computational tool that enables machines to learn from experience, adapt to new data, and execute tasks similarly to humans [146]. The success of vertical farming is intricately tied to technology, with automation and AI at the forefront of transformative innovations in food cultivation [147]. AI, powered by machine-learning algorithms, is employed to analyze information and render decisions. In the context of vertical farming, AI has the capability to monitor plant growth, optimize environmental parameters, and maximize resource usage, including water and fertilizers [146]. By examining data from physical and imaging sensors, AI identifies patterns and forecasts plant health and development, empowering growers to make informed decisions and maximize crop yields [148].

The adoption of emerging technologies is essential for vertical farming in order to mitigate costs and reduce environmental impacts. Vertical farms are embracing innovative solutions to address these challenges [95]. AI plays a significant role in monitoring crop growth in vertical farming, leading to improved production outcomes. For instance, in vertical farming using artificial lighting, color images are utilized for plant phenotyping, enabling continuous monitoring and optimization of crop development [102]. Hwang et al. [148] introduced an image-based system for monitoring crop growth and demonstrated its applicability on real-world vertical farms using a dataset. Vorapatratorn et al. [149] designed an AI-driven automatic control system for plant factories that collects plant-growth data through environmental sensors and cameras. Crop-growth records from multiple planting cycles were stored and used to train machine-learning models for automated plant growth. Rizkiana et al. [150] employed resilient backpropagation ANNs to estimate plant growth, taking into account both environmental factors and the initial heights of the plants. They developed and assessed this model using lettuce cultivation in a plant factory.

To assess leaf stress levels, Story et al. [151] utilized a machine-vision system to detect calcium deficiency in lettuce cultivated in greenhouses. They applied a gray-level co-occurrence matrix (GLCM) to capture textural characteristics and dual segmented regression analysis to distinguish nutrient-deficient plants from healthy plants. Hao et al. [152] developed a multiscale hierarchical convolutional neural network (MFC-CNN) architecture and evaluated its performance across different stress levels. Sun et al. [153] proposed a CNN model for feature extraction from RGB images and combined it with sensor data to estimate water stress in plants, highlighting the effectiveness of CNNs in crop-stress classification. In another study, Gozzovelli et al. [154] used Wasserstein GAN (WGAN) and a deep CNN architecture to locate and identify tip-burn stress in lettuce grown in plant factories. Figure 11 illustrates an application of sensor-based real-time monitoring for growth and stress detection in seedlings employing artificial intelligence algorithms.

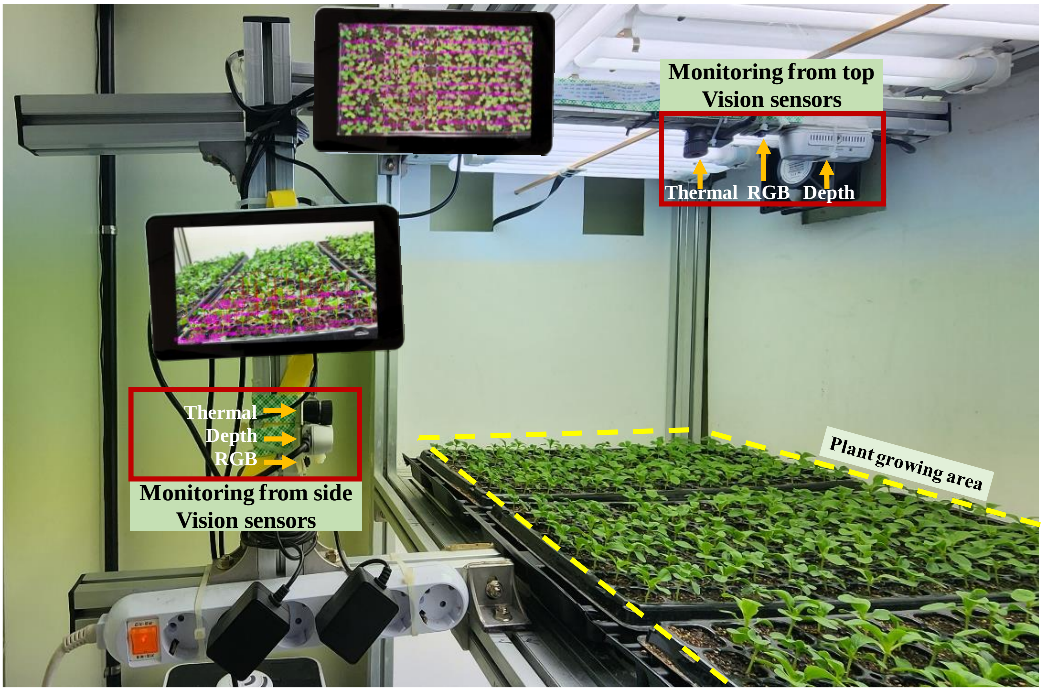

Figure 11. Sensor-based real-time growth and stress detection of seedlings using AI for smart production at the Agricultural Production Machinery and Precision Agriculture Lab, Chungnam National University, South Korea.

Utilizing advanced deep-learning techniques, Wu et al. [155] employed DeepLabV3+ models with various backbones, and they achieved an impressive 99.24% pixel accuracy in segmenting abnormal leaves (yellow, withered, and decayed) in hydroponic lettuce. Hendrawan et al. [156] explored water stress in cultured Sunagoke moss by inducing different conditions in a growth chamber, and they compared deep-learning models for classification. The most effective model, ResNet50, trained with a RMSProp optimizer, achieving 87.50% accuracy. Lee et al. [157] introduced an automated plant-phenotyping system utilizing superpixel-based machine-learning techniques in a controlled chamber for rosette plants. This system uses segmented images to analyze variations in plant parameters over time and offers a user-friendly interface for data learning and visualization. However, estimating plant area through top-view images may be prone to errors due to the influence of circadian leaf movement. The utilization of AI in vertical farming is summarized in Table 4.

Table 4. Application of AI algorithms for plant monitoring in vertical farming.

Model/Algorithm	Observed Features	Accuracy (%)	Plant Type (Application)	Reference
CNN, ResNet50	Plant leaf	86.0	Lettuce (disease detection and identification)	[146]
3D plant modeling, deep segmentation	Plant height, leaf area, leaf weight	-	Basil (phenotyping)	[102]
Mask-RCNN with pseudo crop mixing	Leaf area	76.9	Lettuce (growth monitoring)	[148]
ANN algorithm, big data	Plant growth	98.32	Lettuce (growth prediction)	[149]
ANN, backpropagation	Plant height	72.8	Lettuce (growth prediction)	[150]
Dual segmented regression	Plant leaf	97.0	Lettuce (leaf stress)	[151]
MFC-CNN	Plant leaf	87.95	Lettuce (leaf stress)	[152]
CNN, ResNet26	Plant leaf	91.78	Mix plants (plant stress)	[153]
WGAN, deep CNN architectures	Plant leaf	87.0	Lettuce (leaf stress)	[154]
DeepLabV3+	Plant leaf	83.26	Lettuce (leaf abnormalities)	[155]
Deep-learning models	Plant leaf	94.15	Moss (water stress)	[156]
RF, SVM, MLP	Plant leaf	95.3, 72.9, 84.4	Rosette (phenotyping)	[157]
InceptionResNetv2, Xception, DarkNet 53	Plant leaf	82.0, 75.0, 98.0	Lettuce (phytomorphological attributes)	[158]
LSSVM	Plant leaf	99.0	Wheat (water stress)	[159]
Neural network, SVM classifier	Plant growth	80.0	Strawberry (disease detection)	[160]
Viola–Jones algorithm, Haar	Fruit	-	Tomato (disease detection)	[161]
Self-organizing map (SOM), hierarchical, K-means	Plant leaf	91.3, 98.6, 99.1	Lettuce (growth prediction)	[162]
Logistic regression	Plant growth	97.1	Lettuce (yield)	[163]
KNN algorithm	Plant growth	93.0	Leafy vegetables (growth)	[164]
Reinforcement learning	Plant leaf	82.0	Chili, beans, potatoes, onions (phenotyping)	[165]
MobileNetV2	Plant leaf	98.4	Lettuce (growth prediction)	[166]
U-Net	Leaf area, fresh weight	97.0	Arabidopsis (phenotyping)	[167]
Genetics algorithms, back propagation	Leaf area	99.3	Tomato (LAI)	[168]
DeepFlow, principal-component analysis	Plant area, weight	74.3	Lettuce (growth prediction)	[169]
Deepabv3+	Plant height, coverage	98.2	Lettuce (plant spacing)	[170]

AI is gradually transforming vertical farming by enhancing crop yields, optimizing resource allocation, and automating tasks. However, despite its immense potential, several challenges must be addressed before AI can fully realize its role in vertical farming. Vertical farms generate vast amounts of data from sensors and cameras, which can be costly to collect, store, and process, particularly for small and medium-sized farms [95,146]. A variety of AI algorithms are available for vertical farming, each has its own strengths and weaknesses, and the lack of a standardized software platform can hinder their integration [146,149]. Furthermore, the use of AI raises privacy and security concerns regarding sensitive data about crops, farmers, and consumers [154,171].

Data quality is essential for AI accuracy and performance but can be challenging to ensure due to sensor noise, environmental variability, and human error [169,172]. Training and deploying AI models can be resource intensive, posing challenges for small and medium-sized vertical farms [168,169]. However, understanding how AI models make decisions is crucial, especially for decision-making tasks where transparency is essential for food safety and quality [168,169]. Addressing bias in AI models is vital to ensure fairness and accuracy in decision making [152,171]. Despite these challenges, AI has the potential to revolutionize vertical farming, making it more efficient, productive, and sustainable. By addressing these issues and continuing to refine and integrate AI techniques, vertical farming can significantly contribute to global food security, resource conservation, and environmental stewardship. Navigating this exciting frontier will require concerted efforts in terms of collaboration, innovation, and thoughtful policies to unlock the full potential of AI to reshape the future of vertical farming.

4. Global Industrial and Market Trends

4.1. Global Status

Vertical farming has gained momentum globally as an innovative and sustainable approach to agricultural production. Offering the unique ability to cultivate crops in vertically stacked layers, this cutting-edge technique is reshaping traditional farming practices and making significant progress in meeting the growing demands of a rapidly changing world [173]. Global food consumption and population growth are driving the need for innovative food-production methods. Vertical farming, with its ability to produce crops efficiently in controlled environments, is addressing this demand, contributing to the growth of controlled-environment food production [174].

Globally, there is a growing number of companies engaged in small-scale vertical farming ventures. In Europe, Asia, and North America, countries have adopted commercial vertical farming for high-yield crop cultivation in controlled indoor settings [27]. Unlike traditional methods, vertical farming involves monitoring and controlling all aspects, including artificial lighting, to maximize space efficiency [14,175]. These farms, which can be found underground, on rooftops, or in abandoned spaces of urban areas, employ distinct technologies for specific microenvironments, with a focus on leafy vegetable production [176]. The regions leading the adoption of vertical farming are East and Southeast Asia and North America, including China, Japan, Singapore, South Korea, the USA, and Canada [33]. These regions prioritize advanced technology and local crop commercialization in urban areas. Numerous urban centers have promoted vertical farming initiatives, aiming to address the challenges of sustainable food production. Below is a brief overview, while Tables 5–7 provide lists of these vertical farming projects.

Table 5. Leading vertical farms in production across Asia.

Vertical Farm, Location	Types of Crops	Production Capacity	Cultivation System	Technical Features	Website
Shinnippo Ltd. 808 Factory, Shizuoka, Japan	Mainly lettuce (frilly, green leaf, silky, and romaine)	• First factory: 10,000 heads of lettuce daily; • Second factory: 20,000 heads of lettuce daily.	• First: DFT; • Second: NFT.	• Manual/semiautomated sowing; • Automated transplanting, packing; • Automated conveying (only in second factory).	https://www.808factory.jp/ (accessed on 7 March 2023)

Table 5. *Cont.*

Vertical Farm, Location	Types of Crops	Production Capacity	Cultivation System	Technical Features	Website
Spread Co., Ltd., Kyoto, Japan	Leafy greens (lettuce), strawberries	• Techno Farm Narita: 30,000 heads of lettuce daily; • Techno Farm Fukuroi: 10 tons daily; • Kameoka Plant: 21,000 heads of lettuce daily; • Techno Farm Keihanna: 30,000 heads of lettuce daily.	DFT	• Techno Farm Keihanna • Automated cultivation utilizing IoT/AI technologies; • Technologies for environmental control and water reuse; • Specialized LED lights.	https://spread.co.jp/en/ (accessed on 7 March 2023)
Mirai Co. Ltd., Chiba, Japan	Greenleaf, kale, oakleaf, spinach, basil	• 16,000 heads of greenleaf per day	DFT	• Sensor-based monitoring and control; • Special-purpose LED.	https://miraigroup.jp/ (accessed on 7 March 2023)
N.Thing, Seoul, South Korea	Salad vegetables	• 3 tons of lettuce per cultivation module	Modular hydroponics	• Crops grown in Cube, an IoT-based container; • Developing cultivation systems and systems for new crops.	https://nthing.net/ (accessed on 10 February 2023)
NextOn, Seoul, South Korea	Special leafy vegetables (caipira, ezatrix, Isabelle), herbs, strawberries, biomaterial	• Daily output of health-functional ingredients of up to 1 ton	Smart hydroponics	• Automated lift, seeding, and transport systems; • World's largest underground vertical farm built inside an abandoned tunnel.	http://nexton.ag/farm/index.php (accessed on 7 March 2023)
Farm8, Gyeonggi-do, South Korea	Salad vegetables, special vegetables (herbs, asparagus, minivegetables, etc.)	• Collaborates with 70 farms and distributes nearly 40 tons of packaged salads daily	Hydroponics	• Shipping container-type vertical farm; • Creates vertical farms for subway stations.	http://en.farm8.co.kr/ (accessed on 10 February 2023)
SANANBIO, Fujian, China	Leafy greens, fruits, microgreens, herbs, medicinal plants, edible flowers, etc.	• Leafy greens: 400 kg/set/year (6-layer Radix); • Cucumber: 200 kg/set/year (1-layer Radix); • Microgreens: 350 kg/set/year (6-layer Radix).	NFT-DWC hybrid irrigation	• Modularized and container cultivation systems; • Utilizes a hybrid NFT and DWC system and implements customized light recipes for specialized applications.	https://www.sananbiofarm.com/ (accessed on 7 March 2023)

Table 6. Leading vertical farms in production across the USA.

Vertical Farm, Location	Types of Crops	Production Capacity	Cultivation System	Technical Features	Website
80 Acres Urban Agriculture limited liability company (LLC), Ohio, USA	Lettuce, rocket (arugula), kale, basil, microgreens	90,718.4 kg/year	NFT	• Closed-loop farming; • Robotics equipment is specialized for tasks like seeding, transplanting, and harvesting crops.	https://www.80acresfarms.com/ (accessed on 12 April 2023)
AeroFarms, New Jersey, USA	Baby bok choy, spinach, and micro arugula, broccoli, and kale	907,184 kg/year	Aeroponics	• Closed-loop system; • Specific light spectrum.	https://www.aerofarms.com/ (accessed on 7 March 2023)
American Hydroponics, California, USA	Leafy greens, herbs, tomatoes, peppers, cucumbers		NFT, Bato bucket, and gutter	• Seed-propagation system; • Plant-usable light system.	https://amhydro.com/ (accessed on 7 March 2023)

Table 6. *Cont.*

Vertical Farm, Location	Types of Crops	Production Capacity	Cultivation System	Technical Features	Website
Bright Farms, New York, USA	Lettuce, butterhead lettuce, baby spinach, basil, chickpeas		Hydroponics	• Purple LED grow lights; • Computer-controlled system.	https://www.brightfarms.com/ (accessed on 31 May 2023)
Gotham Greens, New York, USA	Lettuces, herbs	136,000 kg/year	NFT	• L1000 PPB lighting	https://www.gothamgreens.com/ (accessed on 7 March 2023)
Plenty Unlimited, California, USA	Lettuce		Hydroponics	• Watering system recycles evaporated water for plant nourishment; • Robots and conveyors transport plants between destinations.	https://www.plenty.ag/ (accessed on 26 August 2023)
Bowery Farming, New York, USA	Leafy greens, lettuce, herbs, tomatoes		Aeroponics	• Sensor- and AI-based monitoring	https://bowery.co/ (accessed on 26 August 2023)
Altius Farms, Washington, USA	Variety of leafy greens, herbs		Aeroponics	• Special grow lights	https://altiusfarms.com/ (accessed on 7 March 2023)
Green Spirit Farms, Colorado, USA	Variety of leafy greens, herbs	38,100 kg/year	Aeroponics	• LED climate chamber	https://www.greenspiritliving.com/https://altiusfarms.com/ (accessed on 7 March 2023)

Table 7. Leading vertical farms in production across Europe.

Vertical Farm, Location	Types of Crops	Production Capacity	Cultivation System	Technical Features	Website
PlantLab, Hertogenbosch, Netherlands	Lettuce, basil, mint, coriander, fresh-cut herbs, tomatoes	-	Aeroponics	• Specially developed LEDs	https://plantlab.com/ (accessed on 15 April 2023)
Jones Food Company, North Lincolnshire, England	Lettuce, cress, komatsuna, hazel, basil, coriander, parsley, mint, dill, rocket, strawberries	136,078 kg/year	Aeroponics	• Utilizes renewable energy; • Purple LED grow lights.	https://www.jonesfoodcompany.co.uk/ (accessed on 7 March 2023)
Agricool, Paris, France	Strawberries, basil, arugula	-	Aeroponics	• Climate-controlled containers	https://www.agritecture.com/agricool (accessed on 7 March 2023)
Infarm, Berlin, Germany	Lettuce, tomatoes, cucumbers, herbs, microgreens, mushrooms, leafy greens	-	Aeroponics	• Centrally controlled using cloud service and AI	https://www.infarm.com/ (accessed on 2 June 2023)
B-Four Agro, Warmenhuizen, Netherlands	Leafy greens, lettuce, kale, spinach	-	Aeroponics	• Solar-powered LED system; • Automated seeding.	https://b4agro.nl/ (accessed on 15 April 2023)
Byspire, Oslo, Norway	Lettuce, kale, spinach	50,000 plants/year	Aeroponics	• LED climate chamber	https://www.byspire.no/ (accessed on 7 March 2023)

Table 7. *Cont.*

Vertical Farm, Location	Types of Crops	Production Capacity	Cultivation System	Technical Features	Website
CityFarm, Stockholm, Sweden	Lettuce, arugula, basil	-	Closed-loop aeroponics	• LED climate chamber	www.cityfarmer.org (accessed on 7 March 2023)
Delicious, Beesel, Netherlands	Lettuce	-	Aeroponics	• LED climate chamber; • Rainwater recycling.	https://www.deliscious.eu/ (accessed on 7 March 2023)
Farmers Cut, Hamburg, Germany	Leafy greens, microgreens, herbs, cress	400 kg/day	Aeroponics	• Automated climate control; • Special growth medium.	https://farmerscut.com/ (accessed on 2 June 2023)
Future Crops, Poeldijk, Netherlands	Herbs, lettuce, baby lettuce, basil, cilantro, parsley	77,100 kg/year	Aeroponics	• Purple LED grow lights	http://www.future-crops.com/ (accessed on 7 March 2023)
BrightBox, Venlo, Netherlands	Lettuce, arugula, basil	-	Aeroponics	• Automated climate control; • Solid-state LED lighting.	https://brightbox-venlo.nl/en/ (accessed on 7 March 2023)
Urbanika Farms, Kraków, Poland	Lettuce, arugula, basil	-	Hydroponics	• Mineral wool used as growth medium; • Specialized controlled ecosystem.	https://www.urbanikafarms.com/ (accessed on 7 March 2023)

4.2. Industry and Market Trends in Asia

Vertical farming has gained significant attention in Japan as a solution to the country's agricultural challenges. In 2015, Japan's smart agriculture market was valued at less than USD 90 million, but it is predicted to exceed USD 450 million by 2026 [177]. Over 200 vertical farms in Japan are growing vegetables like tomatoes, bell peppers, lettuce, and broccoli. In 2019, Japan led the world in plant factories equipped with artificial light (PFALs). Tokyo-based companies like Spread Co., Ltd., Kyoto, Japan and Mirai Co., Ltd., Gifu Prefecture, Japan produce thousands of heads of lettuce daily. Techno Farm Keihanna, operated by Spread, uses fully automated labor and yields 30,000 heads of lettuce daily. Mirai utilizes 17,500 LED lights to produce 16,000 heads of lettuce daily. These farms are reducing food waste, boosting the domestic vegetable supply, reducing imports, and aiding disaster-stricken regions while exporting their technology.

Japan aims for 45% food self-sufficiency, with vertical farming supported by big-data-driven production systems [178]. Firms like Pasona and Itoya incorporate vertical farms in urban spaces, offering an innovative solution for city food production [179,180]. Vertical farming in Japan dates back to the 1970s but was scaled up in 2010 with energy-efficient LED lights and government support [180]. The future will see advancements like Techno Farm Fukuroi, set to be the world's largest automated vertical farm, producing 10 tons of lettuce daily. Vertical farming addresses Japan's agricultural challenges by securing food supplies, supporting an aging workforce, and mitigating natural disasters. This innovative approach has the potential to revolutionize agriculture in Japan and offers lessons for global urban food production.

In China, there are approximately 250 active vertical farming sites, and the number is steadily rising [181]. SANANBIO, a prominent leader in Chinese vertical farming, has successfully cultivated over 300 varieties of leafy greens, fruits, medicinal herbs, and edible flowers within their facilities [182]. AgriGarden, established in 2002 as a modern agricultural supply-chain service provider in Beijing, offers comprehensive support, from project consultancy to operations, for urban agriculture and vertical farms [176]. JingDong Group partnered with Mitsubishi Chemical Holdings in 2018 to create a vertical farm in

TongZhou, Beijing, that conserves water and has achieved zero emissions. BEO Technology Group, known for electronic components, has a 4500 m^2 artificial light-based plant factory in Beijing that utilizes AI technology for smart cultivation and monitoring [183]. Large-scale commercial vertical farming is not common in China, but AgriGarden has partnered with real estate firms, local governments, and educational institutions on over 100 vertical farming projects, including small installations in subway stations. Despite the rapid growth of the industry, this sector still represents a small share of food demand and supply [181,183].

Sky Greens in Singapore, the world's pioneering low-carbon, hydraulic-driven vertical farm, began commercial operations in 2012 [176]. The innovative A-Go-Gro technology employs rotating A-shaped towers with up to 26 growing levels, occupying just six square meters of space [184]. Over 120 towers near Singapore's central district currently yield two tons of vegetables daily, with plans for an additional 300 towers and international sales of USD 10,000 per tower. This system contributes 10% of Singapore's vegetable market, enhancing food security and sustainability [28].

South Korean agriculture is increasingly embracing technology, particularly vertical farming. Suwon, a 450 m^2 vertical urban-farming prototype, demonstrates advanced techniques for growing and analyzing vegetables. It is a scientific experiment led by the Rural Development Administration that utilizes renewable energy sources for heating, cooling, and lighting [185]. Recent developments in South Korea's vertical farming industry showcase the emergence of smart vertical farms like N.Thing, NextOn, Farm 8, and ALGA Farmtech [186]. NextOn [187] transformed an abandoned highway tunnel into the world's largest tunnel-type indoor farm (approx. 6700 m^2) and uses LED lights and classical music to optimize plant growth [186]. Meanwhile, Farm8 [188] introduced Metro Farms in Seoul subway stations, partnering with the city government to grow various vegetables [188]. N.Thing's [189] CUBE is a technology-driven vertical farm with automated systems that control environmental factors and collect data for optimal crop growth. ALGA Farmtech [190] utilizes ultrahigh-density cultivation (UHDC), achieving three times the productivity of traditional vertical farms. These farms will soon collaborate with data companies to analyze their extensive data for precise plant control, aiming to grow a variety of crops.

4.3. Industry and Market Trends in the USA

The vertical farming market in the USA is on a strong growth trajectory, projected to reach approximately USD 3.21 billion in 2023 and expand to USD 5.37 billion by 2028. This growth corresponds to a compound annual growth rate (CAGR) of around 10.80% during the forecast period of 2023 to 2028 [191]. The US vertical farming market employs various growth mechanisms, including aeroponics, hydroponics, and aquaponics. It includes various structural approaches, such as farms within buildings and vertical farms housed in shipping containers. Additionally, a wide range of crops are cultivated, from fruits and vegetables to herbs and microgreens, flowers, ornamentals, and various other crop types [191].

A leading indoor vertical farming company in the USA, 80 Acres Farms [192] is the nation's first fully automated indoor farm, spanning 13,935 m^2 (Figure 12a). The facility includes a 360 m^2 single-layer growing area using NFT for cultivating crops (Figure 12b). In 2018, their aim was to achieve a daily output of approximately 5000 kg of fresh leafy greens, with a focus on functional or specialty plants like lettuce, rocket (arugula), kale, basil, and microgreens, which are particularly popular in the USA [40]. AeroFarms [47] is another pioneering entity revolutionizing global agriculture through eco-friendly, large-scale, local food production using innovative indoor vertical farming technology. They grow over 400 varieties of greens and herbs, offering Dream Greens for the retail market and AeroFarms for foodservice. Their mission is centered around community-nurtured delicious food with a positive global impact. AeroFarms is at the forefront of technological advancements by automating R&D, optimizing plant traits, and driving innovations in plant science and technology to reduce future farm costs and investments [193].

AmHydro [194] is a pioneer in sustainable hydroponic solutions, enabling global communities to grow fresh and clean local food. They design efficient NFT hydroponic systems for food production, emphasizing water conservation through closed-loop irrigation and offering space and cost savings for growers through the use of powdered nutrients. BrightFarms [195] specializes in supplying local non-GMO and pesticide-free salad greens to supermarkets. They utilize computer-controlled hydroponic systems for cultivation. Hort Americas [196] provides a comprehensive range of growing supplies and accessories for indoor vegetable and specialty crop growers, including those cultivating cut flowers, young plants, tropical plants, herbs, and orchids. Plenty [48] is at the forefront of revolutionizing agriculture through indoor vertical farms, producing pesticide-free greens with minimal water and land use compared to traditional farming. The Plant [197] aims to establish efficient, replicable models that close waste and energy loops, inspiring others to combat climate change by using similar techniques. FarmedHere [198] is dedicated to addressing food sustainability with indoor vertical farming, utilizing aquaponics to save up to 97% of fresh water and produce organic food two to three times faster than traditional methods.

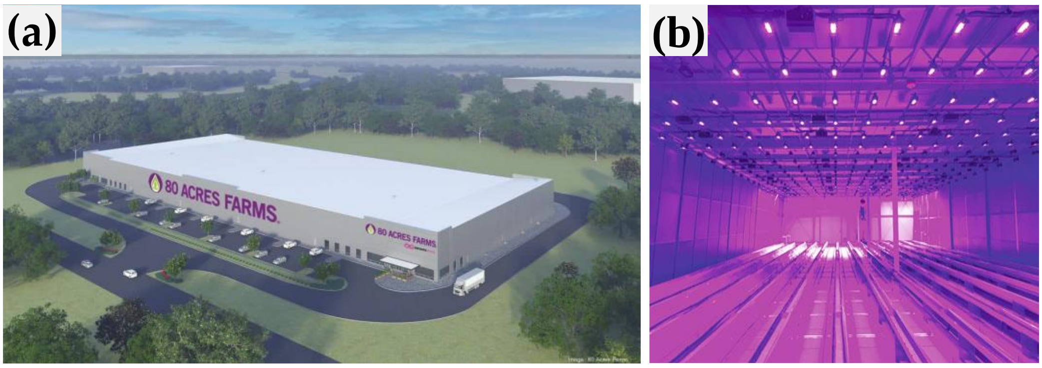

Figure 12. (**a**) Indoor farm operated by 80 Acres Urban Agriculture LLC (adapted from [199]); (**b**) 360 m^2 cultivation system operating with nutrient-film technique (NFT) in Cincinnati, Ohio, USA (adapted from [40]).

4.4. Industry and Market Trends in Europe

In Europe, the term "vertical farm" is preferred over "plant factory" to describe a facility that uses vertically stacked or inclined shelves for intensive plant cultivation [200]. European vertical farms have witnessed rapid growth in recent years, despite starting on a small scale. Several factors are driving this expansion, including reduced costs for LED lighting; growing consumer demand for fresh, healthy, locally grown produce with minimal environmental impact; and the repurposing of vacant office buildings from the 2007–2008 financial crisis. The supply sector supporting vertical farms has also expanded, with both startups and established greenhouse-industry suppliers contributing to this growth. However, there remain uncertainties regarding the cost effectiveness, scalability, and environmental sustainability of intensive vertical farming [201]. The initial investment in vertical farming can be as much as 10 times higher per square meter compared to high-tech greenhouses, while operational costs per square meter are estimated to be two and a half to five times higher than those of Dutch greenhouses [35].

In the Netherlands, organizations like PlantLab, 's-Hertogenbosch, The Netherlands [202], UrbanFarmers, Wallisellen, Switzerland [203], and B-Four Agro, Warmenhuizen, The Netherlands [204] are among the prominent players in the vertical farming sector. These entities have been at the forefront of developing innovative technologies and establishing facilities, often in urban centers, and they cultivate various types of crops, including leafy greens, herbs, and even some fruits. PlantLab is a pioneering Dutch company that is revolutionizing indoor vertical farming. Their exclusive technology enables sustainable cultivation of a variety of leafy vegetables, addressing food crises by growing fresh and pesticide-free produce locally. This approach reduces water usage by 95% and minimizes land requirements. PlantLab primarily focuses on developing and operating large-scale custom indoor farms to transform the global food chain.

UrbanFarmers [203] leads in urban food production and smart sustainable growing systems, producing ultralocal fresh fish and vegetables in cities. Agricool, Paris, France [205], with hydroponic shipping containers in Paris, has assessed the performance of their container farms compared to existing indoor-farming solutions. Infarm, Berlin, Germany [206] offers a sustainable solution to address food security and climate challenges by collecting over 50,000 data points throughout the growth cycle of each plant. This information guides ongoing improvements in growing recipes to enhance yield, quality, and nutritional value while minimizing resource consumption. Farmers Cut [207] introduced Dryponics, a sustainable year-round cultivation method for fresh greens. This innovative approach combines automation, software, and climate control to optimize plant growth. It offers efficiency, modularity, and flexibility, making it a superior choice for global farm networks compared to traditional methods. A summary of some of the most prominent vertical farming companies in Europe is provided in Table 7.

4.5. Innovative Concepts for Upcoming Vertical Farms

Numerous proposals for multistory vertical farms remain conceptual due to economic infeasibility. Nevertheless, certain companies are earnestly pursuing visionary concepts and are nearing implementation. Vertical farming, a dynamic and constantly changing industry, has witnessed bankruptcies, like Urban Farmers (Netherlands) in 2018 and Plantagon (Sweden) in 2019, while some businesses have launched or expanded their operations [35]. Table 8 outlines the essential features of upcoming vertical farms.

Sasaki Architects [208] envisions a groundbreaking 100-hectare Sunqiao Urban Agriculture District in Shanghai, China, as a pioneering national agricultural zone. The plan elevates the district's significance by integrating food networks, vertical farming, research, education, civic areas, and markets. This innovative integration fosters hyperlocal consumption, allowing residents to procure produce from their own buildings, which promotes sustainability. In that regard, Despommier [27] suggested that such buildings adopt circular economy features like rainwater harvesting and solar panels, which would reduce water use and waste, particularly in consistently sunny regions.

Using a similar concept, La Tour Vivante [209], designed by SOA Architects, integrates agriculture, living, and activities vertically, densifying the city while promoting autonomy through localized farming. This unique design fosters energy-efficient living and work by combining various functions in integrated spaces, achieving a symbiotic relationship between urban living and agriculture.

Jian Mu Tower by CRA-Carlo Ratti Associati includes a vertical hydroponic farm that yields 270,000 kg of food annually for 40,000 people. The 218 m Shenzhen tower also houses offices, a supermarket, and a food court. In collaboration with ZERO, an Italian agricultural innovation company, an AI-powered "virtual agronomist" manages daily farm operations, and inner gardens provide relaxation space. A mobile app allows office workers to adjust their environment [210]. The Harvest Green Tower [211] by Romses Architects won Vancouver's 2030 Challenge for its proposal for a multiuse vertical farm tower addressing climate change and urban growth. It integrates vertical farming of crops and livestock with renewable energy from wind, solar, and geothermal sources. The tower's design features photovoltaic glazing, wind turbines, and compost-based energy. The versatile design includes residential, office, retail, and entertainment spaces while promoting high-density urban development. By promoting high-density mixed-use urban centers, the project aligns with the city's climate goals and urban planning [212].

The Urban Skyfarm [213], a winner of the 2013 Green Dot Design Competition, presents an innovative vertical farming concept for urban areas like downtown Seoul, South Korea. Inspired by towering trees, the aim is to enhance local food production, environmental quality, and renewable energy generation. This vertical farm features sections resembling root, trunk, branch, and leaf components, each catering to various farming needs. By elevating the main vegetation area, it maximizes sunlight exposure and outdoor farming space. The Skyfarm also functions as a community garden hub, fostering engagement and local trade. As a net-zero facility, it relies solely on solar and wind energy, while its ecological features contribute to air and water filtration, green-space expansion, and reduced urban heat and runoff [214].

Another vertical farm, designed by DLR Bremen, has 37 floors covering 0.93 ha to feed 15,000 people. The tower includes 25 crops and 3 aquaculture floors, plus 3 for environmental control and 2 for waste management in the basement. Additionally, a floor is designated for cleaning trays and germination, while another handles vegetable and fish packing and processing. This 167.5 m high, 44 m long tower uses 217,000 L of water daily, with most of it recycled. The system is aimed at achieving sustainable food production and addressing contamination challenges in a controlled environment [22]. Spread [215] aims to create a sustainable society under the global food-infrastructure concept, ensuring peace for future generations. Since its inception, Spread has pursued this goal, and the company is currently focused on achieving its objective of producing 100 tons of lettuce daily within the country by 2030. To address global food demand, Spread is diversifying with fruits and alternative meats and envisioning future expansion, aiming to alleviate food concerns worldwide.

Another interesting concept for modular vertical farms involves the use of repurposed shipping containers as farming modules in urban areas, such as Hive-Inn^{TM} City Farm [216]. These containers create an ecosystem in which each unit contributes to food production, energy harvesting, and waste-water recycling. The design incorporates rainwater harvesting, aquaponics, waste composting, methane generation from waste, and solar/wind energy production. This innovative approach aims to bring agriculture closer to urban consumers while efficiently utilizing space and resources for sustainable cultivation of fresh produce in city centers [217]. Future buildings will imitate trees, enabling decentralized food production on conventional grids. Supermarkets could incorporate indoor growing systems, offering fresh produce ordered via apps. This kind of vertical farming would benefit climate mitigation efforts, curb resource waste, and improve health and productivity, offering a brighter urban future [27]. Figure 13 presents conceptual designs for forthcoming vertical farms, providing descriptions of innovative design approaches in their planning and development.

Table 8. Key features of upcoming vertical farms.

Vertical Farm, Location	Company	Key Features	Reference
Sunqiao Urban Agricultural District, Shanghai, China	Sasaki Architects, Boston, USA	• One of China's first comprehensive national agricultural zones; • Enhances district's part in Shanghai's food network by integrating vertical farming, research, and education in a vibrant public area.	[208]
La Tour Vivante, Rennes, France,	SOA Architectes, Paris, France	• 30-floor multiuse vertical farm; • Recycles food waste, exchanges oxygen and CO_2 between plants and tenants, collects rainwater, and generates power for sustainability; • Tower recycles blackwater for plant fertilization; features wind turbines, solar panels, and thermal control; and merges architecture with agriculture.	[209]

Table 8. *Cont.*

Vertical Farm, Location	Company	Key Features	Reference
Jian Mu Tower, Shenzhen, China	Carlo Ratti Associati, Turin, Italy	• 218 m tall tower with 10,000 m^2 of dedicated growing space; • Anticipated annual food production of around 270,000 kg, capable of feeding 40,000 people; • AI-driven "virtual agronomist" manages daily operations.	[210]
Urban Skyfarm, Seoul, South Korea	Aprilli Design Studio, Toronto, Canada	• Offers 44,000 m^2 outdoor farming space, 28,000 m^2 indoor farming, and 3200 m^2 solar panels for energy; • Multilevel layout accommodates outdoor hydroponic fruit trees and indoor crops under artificial lighting; • Net-zero facility that operates only with renewable energy.	[213]
Hive-Inn™ City Farm, New York, USA	OVA Studio Ltd., Sheung Wan, Hong Kong	• Containers repurposed as farming modules in a modular agricultural setup; • Planned features include rainwater collection and reuse of aquaponics–hydroponics water; • Converts waste to compost and methane using solar/wind systems for power generation;	[216]

(**a**) (**b**) (**c**) (**d**)

Figure 13. Conceptual designs of upcoming vertical farms: (**a**) Sunqiao Urban Agricultural District, combining vertical farming systems (adapted from [208]); (**b**) conceptual design of Urban Skyfarm (adapted from [213]); (**c**) La Tour Vivante (the Living Tower) (adapted from [209]); and (**d**) conceptual design of Jian Mu Tower (adapted from [210]).

5. Issues and Future Prospects

5.1. Opportunities and Challenges Regarding Crops, the Environment, and Economics

5.1.1. Crop-Production Perspective

Vertical farming presents promising opportunities for cultivating a diverse array of crops, including leafy greens, fruits, vegetables, and flowers, within controlled environments. This technology holds immense potential to ensure year-round, high-quality produce irrespective of external conditions, while optimizing resource consumption [28,184,218]. The controlled setting of virtual farms allows for the exploration of novel crops, pharmaceutical plants, and niche markets, leveraging the advantages of low disease pressure and regulated conditions [219–221]. By emphasizing the breeding of improved cultivars with compact growth, shorter growth cycles, and early flowering, vertical farming can enhance resource efficiency and yields [218,222]. Advanced technologies further empower efficient crop cultivation, while the shift toward environmental modification augments the capacity for agricultural sustainability and resilience [36]. This technology-driven approach offers the possibility of expanding the horizons of crop cultivation, ensuring food security and enabling novel market opportunities.

Despite its potential, there are challenges in vertical farming in terms of limited crop diversity and the need for specialized cultivars, which affects its adaptability. Breeding improved cultivars with traits like compact growth, shorter growth cycles, and early flowering is essential to address this issue [222]. While vertical farming allows year-round production and optimized resource utilization, its viability is currently confined to specific crops due to growth cycles, spatial constraints, and economic factors [28,223]. Therefore, while vertical farming offers substantial advantages, including efficient resource utilization and consistent production, these challenges underscore the need for strategic solutions to broaden its scope and viability across diverse crops.

5.1.2. Environmental Perspective

Vertical farming offers unique opportunities to enhance environmental sustainability in agriculture. This innovative approach has a lower environmental impact in terms of reduced pesticide and nutrient emissions, minimized water and land usage, and decreased food transport mileage [16,224]. To amplify its role in the food supply chain, it is essential to address initial capital and operational expenses. This can be achieved by refining system design for cost efficiency, optimizing resource utilization, and adopting circular systems [43]. Developing water-saving recycling techniques and localized irrigation systems and harnessing solar power for clean energy can foster self sufficiency and global accessibility in vertical farming, thereby contributing to a sustainable food future [28,225].

Vertical farming faces challenges in managing crucial environmental factors. The precise control of temperature, light, humidity, and other factors demands energy-intensive systems. Energy-intensive operations raise sustainability concerns, necessitating optimized energy sourcing. Challenges in air distribution within closely spaced racks can lead to uneven climate, hampering growth. Crop diseases can spread rapidly in confined spaces, necessitating strict disease-management protocols [219]. Furthermore, the transition from genetic to environmental modification demands advanced technologies and may produce unforeseen ecological impacts [36]. Overcoming these challenges and advancing the technology to effectively control and adapt to environmental conditions will be instrumental in harnessing the full potential of vertical farming for sustainable and efficient food production.

5.1.3. Economic Perspective

Economic considerations predominantly drive the advancement of vertical farming. While the initial investment is high, advantages like reduced transport, resource efficiency, and climate resilience make vertical farming economically viable in the long run. The controlled environment minimizes susceptibility to pests and diseases, reducing the need for pesticides [219]. The close proximity to consumers reduces transportation costs, and the adaptability to various crops provides versatility [28]. The primary drawback of vertical farming is increased electrical energy consumption, but harnessing renewable energy sources can capitalize on the distinct advantages regarding resource utilization, quality enhancement, and automation. Furthermore, cutting-edge automation and AI technologies promise cost reduction, risk mitigation, efficiency, and quality enhancement while optimizing energy-intensive operations [221,226].

The creation of a vertical farm comes with numerous inherent challenges, both economic and practical [227]. The main challenge involves conducting a cost–benefit analysis. The cost of urban land hinders urban vertical farming due to energy costs and optimal environmental maintenance challenges [226]. The considerable initial costs and energy required to construct a vertical farm constitute a fundamental problem, and this may potentially be a reason why vertical farms are not more widespread. Vertical farming also requires substantial investments in nutrient delivery systems, crop-growing platforms, and growth equipment, leading to significantly higher costs, which can be seen as a disadvantage [22]. Locating suitable urban spaces for vertical farming is challenging due to the limited accessibility of land, but this can be addressed by repurposing vacant buildings [228]. A high initial investment may be required when acquiring real estate in a central business district to establish a vertical farming operation [184]. Furthermore, the successful maintenance of vertical farms requires personnel with high levels of expertise in various fields, including plant science, agriculture, agronomy, civil planning, architecture, engineering, economics, and public health [224]. However, as a solution to future food scarcity, vertical farming is expected to become a trend, and reusing existing building structures will eventually reduce the cost [223]. Especially in subtropical countries, the adoption of vertical farming can lead to substantial positive economic enhancement [25]. In the context of globalization, there is an increasing focus on fostering highly adaptable local economies, and urban vertical farming exemplifies this localized initiative, aligning with the broader economic agenda.

5.2. Opportunities and Challenges for Global Food Security

Accelerating urbanization, coupled with the escalating impacts of climate change, land degradation, pandemics, depleted biodiversity, and the extensive utilization of pesticides and fertilizers, has intensified the strain on conventional agricultural systems [5,179]. In this context, vertical farming has emerged as a strong candidate to address these multifaceted challenges and enhance the production of high-quality agricultural yields [43]. This innovative agricultural paradigm represents a transformative strategy with the potential to cultivate fresh and nutrient-rich crops in urban landscapes. Vertical farming can boost yields through faster growth, year-round production, and multitier cultivation, enhancing productivity. Despite the current economic limitations, vertical farming is poised for increased adoption as a proactive response to potential food scarcity. Furthermore, the increasing population and spatial limitations are propelling cities toward becoming megacities.

Responding to this trend, designers around the world are advocating for the use of indoor-farming techniques to realize the potential for urban areas to yield substantial quantities of food [201]. This approach demands less space than conventional farming, fostering urban self-sufficiency in food production while alleviating the strain on land and natural resources [16]. The integration of vertical farming not only addresses current agricultural challenges but also has the potential for ecosystem restoration, offering a sustainable solution to the evolving demands of growing urban populations.

5.3. Technological Opportunities and Challenges

Vertical farming has emerged as a transformative opportunity, blending advanced technologies and innovative cultivation techniques. The integration of hydroponics, aeroponics, and aquaponics, coupled with the precision management of water and nutrients, offers efficient space utilization and reduced environmental impact [93]. Advanced technologies such as AI, sensors, and automation enable precise growth control, reducing resource waste and increasing yields [95,227,229]. With controlled indoor-environment crop cultivation, rapid progress is evident in the evolution of automation, robotics, and artificial intelligence. These advancements enhance food self sufficiency, increase crop yields, and address the challenges of traditional agriculture [16], making vertical farming a promising solution for sustainable food production.

Vertical farming, while promising, faces several technological challenges. The complex integration of cultivation systems in confined spaces demands precise management of water, nutrient delivery, and potential leaks. Maintaining uniform irrigation across multiple tiers is crucial and requires advanced sensor networks and streamlined automation. A synergy between advanced technology and skilled labor is vital, yet there is a shortage of adequately trained personnel. The initial investment is substantial, and the challenges include adapting robotics and automation for delicate crops while maintaining consistent performance [230]. Managing lighting systems for optimal plant growth without producing negative effects is also complex [231]. Furthermore, integrating diverse data streams from sensors demands meticulous calibration and rapid adaptive responses, which involves significant challenges [95]. Challenges also arise from variations among fruits and crops, impacting the effectiveness of robotic systems [232]. However, the potential of vertical farming to enable resource-efficient production, reduced transportation, and controlled environments provides opportunities to overcome the challenges and revolutionize modern agriculture.

6. Conclusions

Vertical farming is a modern agricultural approach that offers exceptional space efficiency, in contrast to conventional farming methods that often result in water wastage and land degradation. The key advantages of vertical farming include the recirculation of freshwater to minimize waste, the optimization of growth conditions for steady year-round harvests, and the ability to sidestep seasonal limitations. These urban-based farms employ advanced technologies to reduce costs by decreasing the need for transportation and labor expenses. However, it is crucial to acknowledge that the realization of vertical farming within urban domains is accompanied by a set of intricate challenges that require careful consideration and strategic resolution. Figure 14 provides a concise overview of the prospects and challenges associated with vertical farming in sustainable food production.

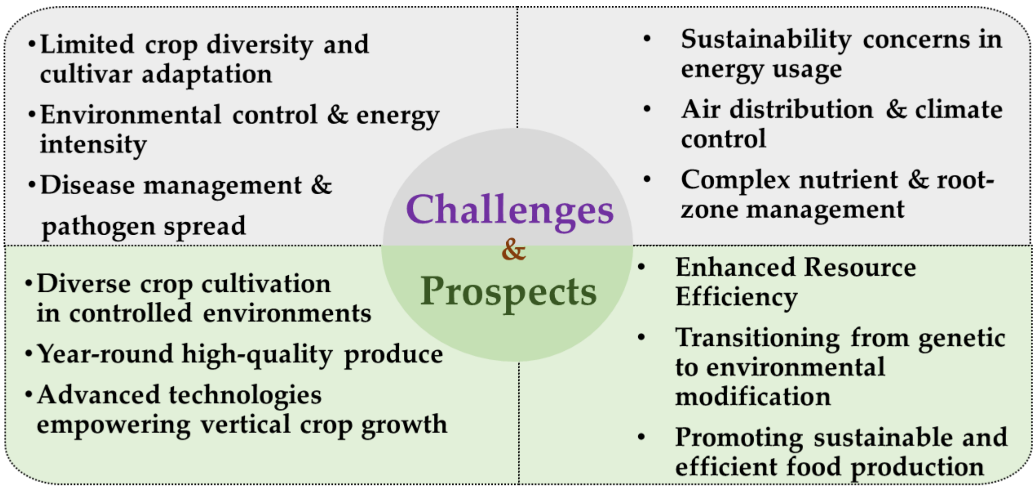

Figure 14. Prospects and challenges of sustainable food production in an urban area.

One of the primary challenges of vertical farming is the substantial expense involved in setup and operation. The infrastructure required for vertical farming, such as controlled environment chambers, advanced lighting systems, and automation technologies, can be costly to install and maintain. Additionally, the increased energy usage of vertical farming operations is a significant concern. A crucial factor contributing to the energy demand is the use of photosynthetic LED lighting, which is essential for plant growth in indoor environments. While renewable energy sources can help mitigate some of the energy-related challenges, they may not always ensure complete farm self-sufficiency, especially if they are incompatible with specific indoor setups. Furthermore, certain crops, such as leafy greens, are better suited for the sustainability goals of vertical farming. Still, challenges arise with cereal crops due to the difficulty in stacking plants and the intense light requirements for their growth.

In contrast, traditional agriculture is struggling to meet rising global food demands due to climate-related factors affecting crop yields and quality. To address this, optimizing the sustainability of farming methods could make traditional practices more efficient despite their significant environmental consequences. While an immediate shift to efficient vertical farming methods would be challenging, a gradual approach that integrates low-carbon methods may align with increasing food needs more sustainably. The feasibility of urban vertical farming has greatly improved in recent years due to emerging technologies. High costs hindered the viability of such farming methods in the past, but the integration of sensors, AI, and robots has transformed the agricultural landscape. Cameras and sensors are employed to monitor factors such as plant growth and disease, with AI analyzing the collected data and providing remedies. Meanwhile, robots have taken on tasks related to harvesting and tending to crops. These technological advancements have significantly reduced the need for human intervention, setting vertical farming apart from conventional practices and safeguarding its economic viability in urban settings.

Vertical farming lacks industry-wide standardization and sustainability certifications due to its evolving technologies and competitive innovations. Establishing standards would enable performance analysis and the dissemination of innovations across the vertical farming industry. Despite the drawbacks and challenges, vertical farms have the potential to promote sustainability, alleviate hunger, and provide local economic support. As technology continues to enhance the efficiency of vertical farming, discussions and debates are initiated about transforming agriculture into a greener, more efficient way of cultivating food, thereby addressing global food demand in a sustainable manner.

Vertical farming is a sustainable and efficient response to the challenges posed by increasing global food demand. Its ability to overcome spatial limitations, ensure year-round production, conserve resources, and embrace technological advancements positions vertical farming as a key player in shaping the future of agriculture. The success and popularity of vertical farming depend on dealing with various regional factors. Local weather, cultural practices, available technology, economic conditions, and government support all contribute to the unique challenges and opportunities encountered by vertical farming initiatives worldwide.

This review explores the dynamic field of vertical farming, covering concepts, classifications, and technological trends, including sensors, IoT, robotics, and AI integration. The assessment extends globally, evaluating the current status of vertical farming as well as the regional technological trends and their impact. In addition, it examines challenges and opportunities in crop production, environmental sustainability, and economic viability, addressing global food security. The aim of this review is to provide a valuable resource for researchers, practitioners, and policymakers seeking to understand and navigate this dynamic field, offering key insights for its future development.

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References

1. United Nations, Department of Economic and Social Affairs, Population Division. *World Population Prospects 2022: Summary of Results (UN DESA/POP/2022/TR/NO.3)*; United Nations: New York, NY, USA, 2022.
2. United Nations, Department of Economic and Social Affairs, Population Division. *World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420)*; United Nations: New York, NY, USA, 2019.
3. Vollset, S.E.; Goren, E.; Yuan, C.-W.; Cao, J.; Smith, A.E.; Hsiao, T.; Bisignano, C.; Azhar, G.S.; Castro, E.; Chalek, J.; et al. Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: A forecasting analysis for the Global Burden of Disease Study. *Lancet* **2020**, *396*, 1285–1306. [CrossRef] [PubMed]
4. Saad, M.H.M.; Hamdan, N.M.; Sarker, M.R. State of the art of urban smart vertical farming automation system: Advanced topologies, issues and recommendations. *Electronics* **2021**, *10*, 1422. [CrossRef]
5. Beacham, A.M.; Vickers, L.H.; Monaghan, J.M. Vertical farming: A summary of approaches to growing skywards. *J. Hortic. Sci. Biotechnol.* **2019**, *94*, 277–283. [CrossRef]
6. Ragaveena, S.; Shirly Edward, A.; Surendran, U. Smart controlled environment agriculture methods: A holistic review. *Rev. Environ. Sci. Biotechnol.* **2021**, *20*, 887–913. [CrossRef]
7. Gan, C.I.; Soukoutou, R.; Conroy, D.M. Sustainability framing of controlled environment agriculture and consumer perceptions: A review. *Sustainability* **2023**, *15*, 304. [CrossRef]
8. Engler, N.; Krarti, M. Review of energy efficiency in controlled environment agriculture. *Renew. Sustain. Energy Rev.* **2021**, *141*, 110786. [CrossRef]
9. Lee, G.O.; Jang, S.-N.; Kim, M.J.; Cho, D.Y.; Cho, K.M.; Lee, J.H.; Son, K.-H. Comparison of growth patterns and metabolite composition of different ginseng cultivars (Yunpoong and K-1) grown in a vertical farm. *Horticulturae* **2023**, *9*, 583. [CrossRef]
10. Nájera, C.; Gallegos-Cedillo, V.M.; Ros, M.; Pascual, J.A. Role of spectrum-light on productivity, and plant quality over vertical farming systems: Bibliometric analysis. *Horticulturae* **2023**, *9*, 63. [CrossRef]
11. Statista. Global Vertical Farming Market Projection 2022–2032. 2023. Available online: https://www.statista.com/statistics/487666/projection-vertical-farming-market-worldwide/ (accessed on 7 August 2023).
12. Li, H.; Guo, Y.; Zhao, H.; Wang, Y.; Chow, D. Towards automated greenhouse: A state of the art review on greenhouse monitoring methods and technologies based on internet of things. *Comput. Electron. Agric.* **2021**, *191*, 106558. [CrossRef]
13. Vatistas, C.; Avgoustaki, D.D.; Bartzanas, T. A systematic literature review on controlled-environment agriculture: How vertical farms and greenhouses can influence the sustainability and footprint of urban microclimate with local food production. *Atmosphere* **2022**, *13*, 1258. [CrossRef]
14. Oh, S.; Lu, C. Vertical farming—Smart urban agriculture for enhancing resilience and sustainability in food security. *J. Hortic. Sci. Biotechnol.* **2023**, *98*, 133–140. [CrossRef]
15. Kalantari, F.; Mohd Tahir, O.; Mahmoudi Lahijani, A.; Kalantari, S. A review of vertical farming technology: A guide for implementation of building integrated agriculture in cities. *Adv. Eng. Forum* **2017**, *24*, 76–91. [CrossRef]
16. Al-Kodmany, K. The Vertical Farm: A review of developments and implications for the vertical city. *Buildings* **2018**, *8*, 24. [CrossRef]
17. Sandison, F.; Yeluripati, J.; Stewart, D. Does green vertical farming offer a sustainable alternative to conventional methods of production?: A case study from Scotland. *Food Energy Secur.* **2023**, *12*, e438. [CrossRef]
18. Yuan, G.N.; Marquez, G.P.B.; Deng, H.; Iu, A.; Fabella, M.; Salonga, R.B.; Ashardiono, F.; Cartagena, J.A. A review on urban agriculture: Technology, socio-economy, and policy. *Heliyon* **2022**, *8*, e11583. [CrossRef]
19. Kozai, T. Towards sustainable plant factories with artificial lighting (PFALs) for achieving SDGs. *Int. J. Agric. Biol. Eng.* **2019**, *12*, 28–37. [CrossRef]
20. Kalantari, F.; Tahir, O.T.; Joni, R.A.; Aminuldin, N.A. The importance of the public acceptance theory in determining the success of the vertical farming projects. *Manag. Res. Pract.* **2018**, *10*, 5–16.
21. Despommier, D. Vertical Farms in Horticulture. In *Encyclopedia of Food and Agricultural Ethics*; Thompson, P.B., Kaplan, D.M., Eds.; Springer: Dordrecht, The Netherlands, 2014. [CrossRef]
22. Banerjee, C.; Adenaeuer, L. Up, up and away! The economics of vertical farming. *J. Agric. Stud.* **2014**, *2*, 40–60. [CrossRef]
23. Van Gerrewey, T.; Boon, N.; Geelen, D. Vertical Farming: The only way is up? *Agronomy* **2022**, *12*, 2. [CrossRef]
24. Waldron, D. Evolution of vertical farms and the development of a simulation methodology. *WIT Trans. Ecol. Environ.* **2018**, *217*, 975–986.
25. Despommier, D. *The Vertical Farm: Feeding the World in the 21st Century*; St. Martin's Press: New York, NY, USA, 2010; pp. 11–16.
26. Kozai, T.; Niu, G. Introduction: Overview and concept of closed plant production system (CPPS). In *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*, 2nd ed.; Kozai, T., Niu, G., Takagaki, M., Eds.; Academic Press: Cambridge, MA, USA, 2019; pp. 3–6. [CrossRef]

27. Despommier, D. Vertical farms, building a viable indoor farming model for cities. *Field Actions Sci. Rep.* **2019**, *20*, 68–73. Available online: http://journals.openedition.org/factsreports/5737 (accessed on 15 January 2023).
28. Benke, K.; Tomkins, B. Future food-production systems: Vertical farming and controlledenvironment agriculture. *Sustain. Sci. Pract. Policy* **2017**, *13*, 13–16. [CrossRef]
29. Despommier, D. The rise of vertical farms. *Sci. Am.* **2009**, *301*, 80–87. [CrossRef]
30. Al-Chalabi, M. Vertical farming: Skyscraper sustainability? *Sustain. Cities Soc.* **2015**, *18*, 74–77. [CrossRef]
31. Fischetti, M. Growing vertical: Skyscraper farming. *Sci. Am.* **2008**, *18*, 74–79. [CrossRef]
32. Benis, K.; Reinhart, C.; Ferrão, P. Building-Integrated Agriculture (BIA) in urban contexts: Testing a simulation-based decision support workflow. In Proceedings of the 15th International Building Performance Simulation Association (IBPSA) Conference, San Francisco, CA, USA, 7–9 August 2017. [CrossRef]
33. Shamshiri, R.R.; Kalantari, F.; Ting, K.C.; Thorp, K.R.; Hameed, I.A.; Weltzien, C.; Ahmad, D.; Shad, Z.M. Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. *Int. J. Agric. Biol. Eng.* **2018**, *11*, 1–22. [CrossRef]
34. Kozai, T. Resource use efficiency of closed plant production system with artificial light: Concept, estimation and application to plant factory. *Proc. Jpn. Acad. Ser. B Phys. Biol. Sci.* **2013**, *89*, 447–461. [CrossRef] [PubMed]
35. Butturini, M.; Marcelis, L.F.M. Vertical farming in Europe: Present status and outlook. In *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*, 2nd ed.; Kozai, T., Niu, G., Takagaki, M., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 77–91. [CrossRef]
36. SharathKumar, M.; Heuvelink, E.; Marcelis, L.F.M. Vertical farming: Moving from genetic to environmental modification. *Trends Plant Sci.* **2020**, *25*, 724–727. [CrossRef]
37. Chole, A.S.; Jadhav, A.R.; Shinde, V. Vertical farming: Controlled environment agriculture. *Just Agric.* **2021**, *1*, 249–256. Available online: https://justagriculture.in/files/newsletter/2021/jan/055.pdf (accessed on 9 August 2023).
38. Chaudhry, A.R.; Mishra, V.P. A comparative analysis of vertical agriculture systems in residential apartments. In Proceedings of the 2019 Advances in Science and Engineering Technology International Conferences (ASET), Dubai, United Arab Emirates, 26 March–10 April 2019. [CrossRef]
39. Kozai, T.; Niu, G. Plant factory as a resourceefficient closed plant production system. In *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*, 2nd ed.; Kozai, T., Niu, G., Takagaki, M., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 93–115. [CrossRef]
40. Kozai, T. Current Status of Plant Factories with Artificial Lighting (PFALs) and Smart PFALs. In *Smart Plant Factory—The Next Generation Indoor Vertical Farms*; Kozai, T., Ed.; Springer: Singapore, 2018; pp. 3–13. [CrossRef]
41. Wong, C.E.; Teo, Z.W.N.; Shen, L.; Yu, H. Seeing the lights for leafy greens in indoor vertical farming. *Trends Food Sci. Technol.* **2020**, *106*, 48–63. [CrossRef]
42. Son, J.E.; Kim, H.J.; Ahn, T.I. Hydroponic systems. In *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*, 2nd ed.; Kozai, T., Niu, G., Takagaki, M., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 273–283. [CrossRef]
43. van Delden, S.H.; SharathKumar, M.; Butturini, M.; Graamans, L.J.A.; Heuvelink, E.; Kacira, M.; Kaiser, E.; Klamer, R.S.; Klerkx, L.; Kootstra, G.; et al. Current status and future challenges in implementing and upscaling vertical farming systems. *Nat. Food* **2021**, *2*, 944–956. [CrossRef]
44. Maucieri, C.; Nicoletto, C.; Os, E.V.; Anseeuw, D.; Havermaet, R.V.; Junge, R. Hydroponic technologies. In *Aquaponics Food Production Systems*; Goddek, S., Joyce, A., Kotzen, B., Burnell, G.M., Eds.; Springer: Cham, Switzerland, 2019; pp. 77–110. [CrossRef]
45. Eldridge, B.M.; Manzoni, L.R.; Graham, C.A.; Rodgers, B.; Farmer, J.R.; Dodd, A.N. Getting to the roots of aeroponic indoor farming. *New Phytol.* **2020**, *228*, 1183–1192. [CrossRef]
46. Lakhiar, I.A.; Gao, J.M.; Syed, T.N.; Chandio, F.A.; Tunio, M.H.; Ahmad, F. Overview of the aeroponic agriculture—An emerging technology for global food security. *Int. J. Agric. Biol. Eng.* **2020**, *13*, 1–10. [CrossRef]
47. Aerofarms. Available online: https://aerofarms.com/ (accessed on 26 August 2023).
48. Plenty. Available online: https://www.plenty.ag/ (accessed on 26 August 2023).
49. Bowery. Available online: https://bowery.co/ (accessed on 26 August 2023).
50. Pala, M.; Mizenko, L.; Mach, M.; Reed, T. Aeroponic greenhouse as an autonomous system using intelligent space for agriculture robotics. In *Robot Intelligence Technology and Applications 2: Results from the 2nd International Conference on Robot Intelligence Technology and Applications*; Kim, J.H., Matson, E., Myung, H., Xu, P., Karray, F., Eds.; Springer International Publishing: Cham, Switzerland, 2014; pp. 83–93. [CrossRef]
51. Lakhiar, I.A.; Gao, J.; Syed, T.N.; Chandio, F.A.; Buttar, N.A. Modern plant cultivation technologies in agriculture under controlled environment: A review on aeroponics. *J. Plant Interact.* **2018**, *13*, 338–352. [CrossRef]
52. Chowdhury, M.; Islam, M.N.; Reza, M.N.; Ali, M.; Rasool, K.; Kiraga, S.; Lee, D.L.; Chung, S.O. Sensor-based nutrient recirculation for aeroponic lettuce cultivation. *J. Biosyst. Eng.* **2021**, *46*, 81–92. [CrossRef]
53. Tunio, M.H.; Gao, J.; Shaikh, S.A.; Lakhiar, I.A.; Qureshi, W.A.; Solangi, K.A.; Chandio, F.A. Potato production in aeroponics: An emerging food growing system in sustainable agriculture forfood security. *Chil. J. Agric. Res.* **2020**, *80*, 118–132. [CrossRef]
54. NGS. New Growing System. Available online: https://ngsystem.com (accessed on 8 April 2023).
55. Omega Garden™. Hydroponics Design. Available online: https://omegagarden.com/ (accessed on 10 July 2023).

56. Farmdominium™. The Farmdominium™ Concept. Available online: https://omegagarden.com/the-farmdominium/ (accessed on 10 July 2023).
57. Sananbio. Indoor Vertical Hydroponic Vegetation Cultivation Module. Available online: https://www.sananbiofarm.com/product/indoor-vertical-hydroponic-vegetation-cultivation-module (accessed on 10 July 2023).
58. Alkhalidi, A.; Jarah, H.; Khawaja, M.K. Innovative design for a portable hybrid system of hydroponic and microalgae to produce food and biofuels. *Clean Energy* **2022**, *6*, 412–423. [CrossRef]
59. Lambert, A. Plant Experience (PX) for Vertical Farming 2.0. Liberty Produce. 28 March 2022. Available online: https://www.liberty-produce.com/post/px-for-vertical-farming (accessed on 9 May 2023).
60. Pocock, T. Light-emitting diodes and the modulation of specialty crops: Light sensing and signaling networks in plants. *HortScience* **2015**, *50*, 1281–1284. [CrossRef]
61. Pattison, P.; Tsao, J.; Brainard, G.; Bugbee, B. LEDs for photons, physiology and food. *Nature* **2018**, *563*, 493–500. [CrossRef] [PubMed]
62. Bantis, F.; Smirnakou, S.; Ouzounis, T.; Koukounaras, A.; Ntagkas, N.; Radoglou, K. Current status and recent achievements in the field of horticulture with the use of light-emitting diodes (LEDs). *Sci. Hortic.* **2018**, *235*, 437–451. [CrossRef]
63. Nwoba, E.G.; Parlevliet, D.A.; Laird, D.W.; Alameh, K.; Moheimani, N.R. Light management technologies for increasing algal photobioreactor efficiency. *Algal Res.* **2019**, *39*, 101433. [CrossRef]
64. Rehman, A.-U.; Abbasi, A.Z.; Islam, N.; Shaikh, Z.A. A review of wireless sensors and networks' applications in agriculture. *Comput. Stand. Interfaces* **2014**, *36*, 263–270. [CrossRef]
65. Singh, N.; Singh, A.N. Odysseys of agriculture sensors: Current challenges and forthcoming prospects. *Comput. Electron. Agric.* **2020**, *171*, 105328. [CrossRef]
66. Sivamani, S.; Bae, N.; Cho, Y. A smart service model based on ubiquitous sensor networks using vertical farm ontology. *Int. J. Distrib. Sens. Netw.* **2013**, *9*, 161495. [CrossRef]
67. Lakhiar, I.A.; Jianmin, G.; Syed, T.N.; Chandio, F.A.; Buttar, N.A.; Qureshi, W.A. Monitoring and control systems in agriculture using intelligent sensor techniques: A review of the aeroponic system. *J. Sens.* **2018**, *2018*, 8672769. [CrossRef]
68. Dhanaraju, M.; Chenniappan, P.; Ramalingam, K.; Pazhanivelan, S.; Kaliaperumal, R. Smart farming: Internet of things (IoT)-based sustainable agriculture. *Agriculture* **2022**, *12*, 1745. [CrossRef]
69. Kato, K.; Yoshida, R.; Kikuzaki, A.; Hirai, T.; Kuroda, H.; Hiwasa-Tanase, K.; Takane, K.; Ezura, H.; Mizoguchi, T. Molecular breeding of tomato lines for mass production of miraculin in a plant factory. *J. Agric. Food Chem.* **2010**, *58*, 9505–9510. [CrossRef]
70. Borgognone, D.; Colla, G.; Rouphael, Y.; Cardarelli, M.; Rea, E.; Schwarz, D. Effect of nitrogen form and nutrient solution pH on growth and mineral composition of self-grafted and grafted tomatoes. *Sci. Hortic.* **2013**, *149*, 61–69. [CrossRef]
71. Trejo-Téllez, L.I.; Gómez-Merino, F.C. Nutrient solutions for hydroponic systems. In *Hydroponics—A Standard Methodology for Plant Biological Researches*; Toshiki, A., Ed.; IntechOpen: Rijeka, Croatia, 2012; pp. 1–22.
72. Bamsey, M.; Graham, T.; Thompson, C.; Berinstain, A.; Scott, A.; Dixon, M. Ion-specific nutrient management in closed systems: The necessity for ion-selective sensors in terrestrial and space-based agriculture and water management systems. *Sensors* **2012**, *12*, 13349–13392. [CrossRef]
73. Kim, H.J.; Kim, W.K.; Roh, M.Y.; Kang, C.I.; Park, J.M.; Sudduth, K.A. Automated sensing of hydroponic macronutrients using a computer-controlled system with an array of ion-selective electrodes. *Comput. Electron. Agric.* **2013**, *93*, 46–54. [CrossRef]
74. Chowdhury, M.; Jang, B.E.; Kabir, M.S.N.; Kim, Y.J.; Na, K.D.; Park, S.B.; Chung, S.O. Factors affecting the accuracy and precision of ion-selective electrodes for hydroponic nutrient supply systems. *Acta Hortic.* **2020**, *1296*, 997–1004. [CrossRef]
75. Chowdhury, M.; Jang, B.E.; Kabir, M.S.N.; Lee, D.H.; Kim, H.T.; Park, T.S.; Chung, S.O. Performance evaluation of commercial ion-selective electrodes for hydroponic cultivation system. *Acta Hortic.* **2020**, *1296*, 831–838. [CrossRef]
76. Jung, D.H.; Kim, H.J.; Choi, G.L.; Ahn, T.I.; Son, J.E.; Sudduth, K.A. Automated lettuce nutrient solution management using an array of ion-selective electrodes. *Trans. ASABE* **2015**, *58*, 1309–1319. [CrossRef]
77. Asaduzzaman, M.; Asao, T. Autotoxicity in strawberry under recycled hydroponics and its mitigation methods. *Hortic. J.* **2020**, *89*, 124–137. [CrossRef]
78. Gutiérrez, M.; Alegret, S.; Caceres, R.; Casadesús, J.; Marfa, O.; Del Valle, M. Application of a potentiometric electronic tongue to fertigation strategy in greenhouse cultivation. *Comput. Electron. Agric.* **2007**, *57*, 12–22. [CrossRef]
79. Jung, D.-H.; Kim, H.-J.; Kim, H.S.; Choi, J.; Kim, J.D.; Park, S.H. Fusion of Spectroscopy and Cobalt Electrochemistry Data for Estimating Phosphate Concentration in Hydroponic Solution. *Sensors* **2019**, *19*, 2596. [CrossRef] [PubMed]
80. Jung, D.H.; Kim, H.J.; Cho, W.J.; Park, S.H.; Yang, S.H. Validation testing of an ion-specific sensing and control system for precision hydroponic macronutrient management. *Comput. Electron. Agric.* **2019**, *156*, 660–668. [CrossRef]
81. Tuan, V.N.; Khattak, A.M.; Zhu, H.; Gao, W.; Wang, M. Combination of multivariate standard addition technique and deep kernel learning model for determining multi-ion in hydroponic nutrient solution. *Sensors* **2020**, *20*, 5314. [CrossRef]
82. Tuan, V.N.; Dinh, T.D.; Khattak, A.M.; Zheng, L.; Chu, X.; Gao, W.; Wang, M. Multivariate standard addition cobalt electrochemistry data fusion for determining phosphate concentration in hydroponic solution. *IEEE Access* **2020**, *8*, 28289–28300. [CrossRef]
83. Zheng, S.; Liu, K.; Xu, Y.; Chen, H.; Zhang, X.; Liu, Y. Robust soft sensor with deep kernel learning for quality prediction in rubber mixing processes. *Sensors* **2020**, *20*, 695. [CrossRef]

84. Cho, W.-J.; Kim, H.-J.; Jung, D.-H.; Han, H.-J.; Cho, Y.-Y. Hybrid signal-processing method based on neural network for prediction of NO3, K, Ca, and Mg ions in hydroponic solutions using an array of ion-selective electrodes. *Sensors* **2019**, *19*, 5508. [CrossRef] [PubMed]
85. Rousseau, C.R.; Bühlmann, P. Calibration-free potentiometric sensing with solid-contact ion-selective electrodes. *TrAC Trends Anal. Chem.* **2021**, *140*, 116277. [CrossRef]
86. Qi, L.; Liang, R.; Jiang, T.; Qin, W. Anti-fouling polymeric membrane ion-selective electrodes. *TrAC Trends Anal. Chem.* **2022**, *150*, 116572. [CrossRef]
87. Popkova, E.G. Vertical farms based on hydroponics, deep learning, and AI as smart innovation in agriculture. In *Smart Innovation in Agriculture*; Popkova, E.G., Sergi, B.S., Eds.; Springer: Singapore, 2022; pp. 257–262. [CrossRef]
88. de Abreu, C.L.; van Deventer, J.P. The application of artificial intelligence (AI) and internet of things (IoT) in Agriculture: A systematic literature review. In *Artificial Intelligence Research*; Communications in Computer and Information Science; Jembere, E., Gerber, A.J., Viriri, S., Pillay, A., Eds.; Springer International Publishing: Cham, Switzerland, 2022; Volume 1551, pp. 32–46. [CrossRef]
89. Ramakrishnam Raju, S.V.S.; Dappuri, B.; Ravi Kiran Varma, P.; Yachamaneni, M.; Verghese, D.M.G.; Mishra, M.K. Design and implementation of smart hydroponics farming using IoT-based AI controller with mobile application system. *J. Nanomater.* **2022**, *2022*, 4435591. [CrossRef]
90. Lowe, M.; Qin, R.; Mao, X. A review on machine learning, artificial intelligence, and smart technology in water treatment and monitoring. *Water* **2022**, *14*, 1384. [CrossRef]
91. Qazi, S.; Khawaja, B.A.; Farooq, Q.U. IoT-equipped and AI-enabled next generation smart agriculture: A critical review, current challenges and future trends. *IEEE Access* **2022**, *10*, 21219–21235. [CrossRef]
92. Crisnapati, P.N.; Wardana, I.N.K.; Aryanto, I.K.A.A.; Hermawan, A. Hommons: Hydroponic management and moni-toring system for an IOT based NFT farm using web technology. In Proceedings of the 2017 5th International Conference on Cyber and IT Service Management (CITSM), Denpasar, Indonesia, 8–10 August 2017; pp. 1–6. [CrossRef]
93. Ullah, R.; Asghar, I.; Griffiths, M.G.; Stacey, C.; Stiles, W.; Whitelaw, C. Internet of things based sensor system for vertical farming and controlled environment agriculture. In Proceedings of the 2023 6th Conference on Cloud and Internet of Things (CIoT), Lisbon, Portugal, 20–22 March 2023; pp. 136–140. [CrossRef]
94. Kaur, G.; Upadhyaya, P.; Chawla, P. Comparative analysis of IoT-based controlled environment and uncontrolled environment plant growth monitoring system for hydroponic indoor vertical farm. *Environ. Res.* **2023**, *222*, 115313. [CrossRef]
95. Morella, P.; Lambán, M.P.; Royo, J.; Sánchez, J.C. Vertical farming monitoring: How does it work and how much does it cost? *Sensors* **2023**, *23*, 3502. [CrossRef]
96. Chowdhury, M.E.H.; Khandakar, A.; Ahmed, S.; Al-Khuzaei, F.; Hamdalla, J.; Haque, F.; Reaz, M.B.I.; Al Shafei, A.; Al-Emadi, N. Design, construction and testing of IoT based automated indoor vertical hydroponics farming test-bed in Qatar. *Sensors* **2020**, *20*, 5637. [CrossRef]
97. Quy, V.K.; Hau, N.V.; Anh, D.V.; Quy, N.M.; Ban, N.T.; Lanza, S.; Randazzo, G.; Muzirafuti, A. IoT-enabled smart agriculture: Architecture, applications, and challenges. *Appl. Sci.* **2022**, *12*, 3396. [CrossRef]
98. Dutta, M.; Gupta, D.; Sahu, S.; Limkar, S.; Singh, P.; Mishra, A.; Kumar, M.; Mutlu, R. Evaluation of growth responses of lettuce and energy efficiency of the substrate and smart hydroponics cropping system. *Sensors* **2023**, *23*, 1875. [CrossRef]
99. Rezk, N.G.; Hemdan, E.E.-D.; Attia, A.-F.; El-Sayed, A.; El-Rashidy, M.A. An efficient IoT based smart farming system using machine learning algorithms. *Multimed. Tools Appl.* **2021**, *80*, 773–797. [CrossRef]
100. Grinblat, G.L.; Uzal, L.C.; Larese, M.G.; Granitto, P.M. Deep learning for plant identification using vein morphological patterns. *Comput. Electron. Agric.* **2016**, *127*, 418–424. [CrossRef]
101. Mehra, M.; Saxena, S.; Sankaranarayanan, S.; Tom, R.J.; Veeramanikandan, M. IoT based hydroponics system using deep neural networks. *Comput. Electron. Agric.* **2018**, *155*, 473–486. [CrossRef]
102. Franchetti, B.; Ntouskos, V.; Giuliani, P.; Herman, T.; Barnes, L.; Pirri, F. Vision based modeling of plants phenotyping in vertical farming under artificial lighting. *Sensors* **2019**, *19*, 4378. [CrossRef] [PubMed]
103. Schima, R.; Mollenhauer, H.; Grenzdörffer, G.; Merbach, I.; Lausch, A.; Dietrich, P.; Bumberger, J. Imagine all the plants: Evaluation of a light-field camera for on-site crop growth monitoring. *Remote Sens.* **2016**, *8*, 823. [CrossRef]
104. Paulus, S.; Behmann, J.; Mahlein, A.-K.; Plümer, L.; Kuhlmann, H. Low-cost 3D systems: Suitable tools for plant phenotyping. *Sensors* **2014**, *14*, 3001–3018. [CrossRef]
105. Mavridou, E.; Vrochidou, E.; Papakostas, G.A.; Pachidis, T.; Kaburlasos, V.G. Machine vision systems in precision agriculture for crop farming. *J. Imaging* **2019**, *5*, 89. [CrossRef]
106. Jiang, G.Q.; Zhao, C.J.; Si, Y.S. A machine vision based crop rows detection for agricultural robots. In Proceedings of the 2010 International Conference on Wavelet Analysis and Pattern Recognition, Qingdao, China, 11–14 July 2010; pp. 114–118. [CrossRef]
107. Paul, K.; Chatterjee, S.S.; Pai, P.; Varshney, A.; Juikar, S.; Prasad, V.; Bhadra, B.; Dasgupta, S. Viable smart sensors and their application in data driven agriculture. *Comput. Electron. Agric.* **2022**, *198*, 107096. [CrossRef]
108. Pérez-Bueno, M.L.; Pineda, M.; Barón, M. Phenotyping plant responses to biotic stress by chlorophyll fluorescence imaging. *Front. Plant Sci.* **2019**, *10*, 1135. [CrossRef] [PubMed]
109. Zahir, S.A.D.M.; Omar, A.F.; Jamlos, M.F.; Azmi, M.A.M.; Muncan, J. A review of visible and near-infrared (Vis-NIR) spectroscopy application in plant stress detection. *Sens. Actuator A Phys.* **2022**, *338*, 113468. [CrossRef]

110. Brzychczyk, B.; Hebda, T.; Fitas, J.; Giełżecki, J. The follow-up photobioreactor illumination system for the cultivation of photosynthetic microorganisms. *Energies* **2020**, *13*, 1143. [CrossRef]
111. Bagha, H.; Yavari, A.; Georgakopoulos, D. IoT-based plant health analysis using optical sensors in precision agriculture. In Proceedings of the 2021 Digital Image Computing: Techniques and Applications (DICTA), Gold Coast, Australia, 29 November–1 December 2021; pp. 1–8. [CrossRef]
112. Qu, C.C.; Sun, X.Y.; Sun, W.X.; Cao, L.X.; Wang, X.Q.; He, Z.Z. Flexible wearables for plants. *Small* **2021**, *17*, 2104482. [CrossRef] [PubMed]
113. Gupta, S.; Huang, C.H.; Singh, G.P.; Park, B.S.; Chua, N.H.; Ram, R.J. Portable Raman leaf-clip sensor for rapid detection of plant stress. *Sci. Rep.* **2020**, *10*, 20206. [CrossRef]
114. Wang, T.; Xu, X.; Wang, C.; Li, Z.; Li, D. From smart farming towards unmanned farms: A new mode of agricultural production. *Agriculture* **2021**, *11*, 145. [CrossRef]
115. Avgoustaki, D.D.; Avgoustakis, I.; Miralles, C.C.; Sohn, J.; Xydis, G. Autonomous mobile robot with attached multispectral camera to monitor the development of crops and detect nutrient and water deficiencies in vertical farms. *Agronomy* **2022**, *12*, 2691. [CrossRef]
116. Blom, T.; Jenkins, A.; Pulselli, R.M.; Van den Dobbelsteen, A.A.J.F. The embodied carbon emissions of lettuce production in vertical farming, greenhouse horticulture, and open-field farming in the Netherlands. *J. Clean. Prod.* **2022**, *377*, 134443. [CrossRef]
117. Kozai, T.; Niu, G. Role of the plant factory with artificial lighting (PFAL) in urban areas. In *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*, 2nd ed.; Kozai, T., Niu, G., Takagaki, M., Eds.; Academic Press: Cambridge, MA, USA, 2019; pp. 7–34. [CrossRef]
118. Eagle Technologies. Use Cases of Factory Automation in Vertical Farming. Factory Automation Food Processing. 2020. Available online: https://eagletechnologies.com/2020/08/03/6-use-cases-of-factory-automation-in-vertical-farming/ (accessed on 12 January 2023).
119. CityCrop. Automated Indoor Farming. Available online: https://citycrop.io/ (accessed on 13 February 2023).
120. Eponic Agriculture Co. Ltd. A Fully Automated Three-Dimensional Vertical Farm Comes into Operation. Available online: https://www.igrowpreowned.com/igrownews/a-fully-automated-three-dimensional-vertical-farm-comes-into-operation (accessed on 16 June 2023).
121. GreenCUBE. Automated Vertical Farming System. Available online: https://tytcorp.com.sg/vertical-cultivation-system/automated-vertical-farming-system (accessed on 18 July 2023).
122. iFarm. iFarm StackGrow Vertical Farming Automation Technology. Available online: https://ifarm.fi/technologies/stack-grow (accessed on 16 July 2023).
123. Seasony. Making the Future of Vertical Farming Profitable, Scaleable, & Sustainable. Available online: https://seasony.io/ (accessed on 12 May 2023).
124. Organifarms. Strawberry Harvesting Robot. 2022. Available online: https://www.organifarms.de/product (accessed on 12 December 2022).
125. IGS. Intelligent Growth Solutions (IGS) Ltd. Growth Towers for Indoor Farming: Fully Automated Year Round Growing. Available online: https://www.intelligentgrowthsolutions.com/product/growth-towers (accessed on 15 June 2023).
126. Badia Farms. The Farm Of The Future, Today. 2018. Available online: https://www.badiafarms.com/ (accessed on 12 May 2023).
127. Techno Farm. Innovation: Vegetable Factory. 2023. Available online: https://www.technofarm.com/en/innovation/ (accessed on 16 March 2023).
128. A-Plus. Farm & Factory TAMURA Plant Factory, Fukushima, Japan. 2021. Available online: https://www.a-plus-tamura.com/farm-factory (accessed on 18 April 2023).
129. Hornayek, T. Chiba Sees Farming Revolution Budding Underground. 2019. Available online: https://shingetsunewsagency.com/2019/02/26/chiba-sees-farming-revolution-budding-underground/ (accessed on 12 February 2023).
130. SANANBIO. Available online: https://www.sananbio.com/ (accessed on 26 February 2023).
131. Allinson, M. Future of Agriculture: What Does Automated Vertical Farming Look Like? 2023. Available online: https://roboticsandautomationnews.com/2023/03/10/future-of-agriculture-what-does-automated-vertical-farming-look-like/64840/ (accessed on 16 July 2023).
132. iFarm. Available online: https://ifarm.fi/ (accessed on 2 March 2023).
133. Iron Ox. Available online: http://ironox.com/ (accessed on 5 March 2023).
134. IGS. Intelligent Growth Solutions (IGS). Available online: https://www.intelligentgrowthsolutions.com/ (accessed on 10 March 2023).
135. Urban Crop Solution. Available online: https://urbancropsolutions.com/ (accessed on 7 March 2023).
136. Lardinois, F. Iron Ox Opens Its First Fully Autonomous Farm. 4 October 2018. Available online: https://techcrunch.com/2018/10/03/iron-ox-opens-its-first-fully-autonomous-farm/ (accessed on 18 August 2023).
137. Marchant, W.; Tosunoglu, S. Robotic implementation to automate a vertical farm system. In Proceedings of the 30st Florida Conference on Recent Advances in Robotics, Florida Atlantic University, Boca Raton, FL, USA, 11–12 May 2107. Available online: https://public.eng.fau.edu/design/fcrar2017/papers/RoboticImplementation.pdf (accessed on 12 February 2023).

138. AgritechTomorrow, Future Crops Brings Vertical Farming Closer to the Land. 2021. Available online: https://www.agritechtomorrow.com/story/2021/12/future-crops-brings-vertical-farming-closer-to-the-land/13356/ (accessed on 10 January 2023).
139. AgriTech. Top 10 Agriculture Trends, Technologies & Innovations for 2023. 2023. Available online: https://www.startus-insights.com/innovators-guide/agriculture-trends-innovation/ (accessed on 16 July 2023).
140. Nokia Bell Labs. Available online: https://www.bell-labs.com/ (accessed on 28 February 2023).
141. ChemistryViews. Vertical Farming with Drones. Wiley-VCH GmbH. 11 August 2021. Available online: https://www.chemistryviews.org/details/news/11313637/Vertical_Farming_With_Drones/ (accessed on 2 March 2023).
142. iFarm. Autonomous Drones Will Help to Observe Plants. Available online: https://ifarm.fi/dron_on_farm (accessed on 18 August 2023).
143. Corvus Drones. Available online: https://www.corvusdrones.com/ (accessed on 20 May 2023).
144. Arugga—AI Farming. Available online: https://www.arugga.com/ (accessed on 20 May 2023).
145. Glick, M. Robotic Bees Could Support Vertical Farms Today and Astronauts Tomorrow. *Sci. Am.* 17 July 2023. Available online: https://www.scientificamerican.com/article/robotic-bees-could-support-vertical-farms-today-and-astronauts-tomorrow/ (accessed on 21 May 2023).
146. Siropyan, M.; Celikel, O.; Pinarer, O. Artificial Intelligence Driven Vertical Farming Management System. In Proceedings of the World Congress on Engineering, London, UK, 6–8 July 2022. Available online: https://www.iaeng.org/publication/WCE2022/WCE2022_pp108-113.pdf (accessed on 15 April 2023).
147. Talaviya, T.; Shah, D.; Patel, N.; Yagnik, H.; Shah, M. Implementation of artificial intelligence in agriculture for optimisation of irrigation and application of pesticides and herbicides. *Artif. Intell. Agric.* **2020**, *4*, 58–73. [CrossRef]
148. Hwang, Y.; Lee, S.; Kim, T.; Baik, K.; Choi, Y. Crop growth monitoring system in vertical farms based on region-of-interest prediction. *Agriculture* **2022**, *12*, 656. [CrossRef]
149. Vorapatratorn, S. Development of Automatic Plant Factory Control Systems with AI-Based Artificial Lighting. In Proceedings of the 2021 13th International Conference on Information Technology and Electrical Engineering (ICITEE), Chiang Mai, Thailand, 14–15 October 2021; pp. 69–73. [CrossRef]
150. Rizkiana, A.; Nugroho, A.P.; Salma, N.M.; Afif, S.; Masithoh, R.E.; Sutiarso, L.; Okayasu, T. Plant growth prediction model for lettuce (*Lactuca sativa*.) in plant factories using artificial neural network. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *733*, 012027. [CrossRef]
151. Story, D.; Kacira, M.; Kubota, C.; Akoglu, A.; An, L. Lettuce calcium deficiency detection with machine vision computed plant features in controlled environments. *Comput. Electron. Agric.* **2010**, *74*, 238–243. [CrossRef]
152. Hao, X.; Jia, J.; Gao, W.; Guo, X.; Zhang, W.; Zheng, L.; Wang, M. MFC-CNN: An automatic grading scheme for light stress levels of lettuce (*Lactuca sativa* L.) leaves. *Comput. Electron. Agric.* **2020**, *179*, 105847. [CrossRef]
153. Sun, Y.; Liu, Y.; Wang, G.; Zhang, H. Deep learning for plant identification in natural environment. *Comput. Intell. Neurosci.* **2017**, *2017*, 7361042. [CrossRef]
154. Gozzovelli, R.; Franchetti, B.; Bekmurat, M.; Pirri, F. Tip-burn stress detection of lettuce canopy grown in Plant Factories. In Proceedings of the IEEE/CVF International Conference on Computer Vision, Montreal, BC, Canada, 11–17 October 2021; pp. 1259–1268. [CrossRef]
155. Wu, Z.; Yang, R.; Gao, F.; Wang, W.; Fu, L.; Li, R. Segmentation of abnormal leaves of hydroponic lettuce based on DeepLabV3+ for robotic sorting. *Comput. Electron. Agric.* **2021**, *190*, 106443. [CrossRef]
156. Hendrawan, Y.; Damayanti, R.; Al Riza, D.F.; Hermanto, M.B. Classification of water stress in cultured Sunagoke moss using deep learning. *TELKOMNIKA Telecommun. Comput. Electron. Control* **2021**, *19*, 1594–1604. [CrossRef]
157. Lee, U.; Chang, S.; Putra, G.A.; Kim, H.; Kim, D.H. An automated, high-throughput plant phenotyping system using machine learning-based plant segmentation and image analysis. *PLoS ONE* **2018**, *13*, e0196615. [CrossRef] [PubMed]
158. Lauguico, S.; Concepcion, R.; Tobias, R.R.; Alejandrino, J.; Guia, J.D.; Guillermo, M.; Sybingco, E.; Dadios, E. Machine Vision-Based Prediction of Lettuce Phytomorphological Descriptors using Deep Learning Networks. In Proceedings of the IEEE 12th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM), Manila, Philippines, 3–7 December 2020; pp. 1–6. [CrossRef]
159. Moshou, D.; Pantazi, X.E.; Kateris, D.; Gravalos, I. Water stress detection based on optical multisensor fusion with a least squares support vector machine classifier. *Biosyst. Eng.* **2014**, *117*, 15–22. [CrossRef]
160. Kim, S.; Lee, M.; Shin, C. IoT-based strawberry disease prediction system for smart farming. *Sensors* **2018**, *18*, 4051. [CrossRef]
161. Anubhove, M.S.T.; Ashrafi, N.; Saleque, A.M.; Akter, M.; Saif, S.U. Machine learning algorithm based disease detection in tomato with automated image telemetry for vertical farming. In Proceedings of the International Conference on Computational Performance Evaluation (ComPE), Shillong, India, 2–4 July 2020; pp. 250–254. [CrossRef]
162. Alejandrino, J.; Concepcion, R.; Lauguico, S.; Tobias, R.R.; Almero, V.J.; Puno, J.C.; Bandala, A.; Dadios, E.; Flores, R. Visual classification of lettuce growth stage based on morphological attributes using unsupervised machine learning models. In Proceedings of the IEEE Region 10 Conference (TENCON), Osaka, Japan, 16–19 November 2020; pp. 438–443. [CrossRef]
163. Gowtham, R.; Jebakumar, R. Analysis and prediction of lettuce crop yield in aeroponic vertical farming using logistic regression method. In Proceedings of the 2023 International Conference on Sustainable Computing and Data Communication Systems (ICSCDS), Erode, India, 23–25 March 2023; pp. 759–764. [CrossRef]

164. Mamatha, V.; Kavitha, J.C. Machine learning based crop growth management in greenhouse environment using hydroponics farming techniques. *Meas. Sens.* **2023**, *25*, 100665. [CrossRef]
165. Obu, U.; Sarkarkar, G.; Ambekar, Y. Computer Vision for Monitor and Control of Vertical Farms Using Machine Learning Methods. In Proceedings of the International Conference on Computational Intelligence and Computing Applications (ICCICA), Nagpur, India, 26–27 November 2021; pp. 1–6. [CrossRef]
166. Jayasekara, C.; Banneka, S.; Pasindu, G.; Udawaththa, Y.; Wellalage, S.; Abeygunawardhane, P.K.W. Automated crop harvesting, growth monitoring and disease detection system for vertical farming greenhouse. In Proceedings of the 3rd International Conference on Advancements in Computing (ICAC), Colombo, Sri Lanka, 9–11 December 2021; pp. 228–233. [CrossRef]
167. Chang, S.; Lee, U.; Hong, M.J.; Jo, Y.D.; Kim, J.B. Time-series growth prediction model based on U-net and machine learning in Arabidopsis. *Front. Plant Sci.* **2021**, *12*, 721512. [CrossRef] [PubMed]
168. Wang, H.; Sánchez-Molina, J.A.; Li, M.; Berenguel, M.; Yang, X.T.; Bienvenido, J.F. Leaf area index estimation for a greenhouse transpiration model using external climate conditions based on genetics algorithms, back-propagation neural networks and nonlinear autoregressive exogenous models. *Agric. Water Manag.* **2017**, *183*, 107–115. [CrossRef]
169. Nagano, S.; Moriyuki, S.; Wakamori, K.; Mineno, H.; Fukuda, H. Leaf-movement-based growth prediction model using optical flow analysis and machine learning in plant factory. *Front. Plant Sci.* **2019**, *10*, 227. [CrossRef]
170. Petropoulou, A.S.; van Marrewijk, B.; de Zwart, F.; Elings, A.; Bijlaard, M.; van Daalen, T.; Jansen, G.; Hemming, S. Lettuce production in intelligent greenhouses—3D imaging and computer vision for plant spacing decisions. *Sensors* **2023**, *23*, 2929. [CrossRef]
171. Galaz, V.; Centeno, M.A.; Callahan, P.W.; Causevic, A.; Patterson, T.; Brass, I.; Baum, S.; Farber, D.; Fischer, J.; Garcia, D.; et al. Artificial intelligence, systemic risks, and sustainability. *Technol. Soc.* **2021**, *67*, 101741. [CrossRef]
172. Vela, D.; Sharp, A.; Zhang, R.; Nguyen, T.; Hoang, A.; Pianykh, O.S. Temporal quality degradation in AI models. *Sci. Rep.* **2022**, *12*, 11654. [CrossRef] [PubMed]
173. Avgoustaki, D.D.; Xydis, G. Indoor vertical farming in the urban nexus context: Business growth and resource savings. *Sustainability* **2020**, *12*, 1965. [CrossRef]
174. Mitchell, C.A. History of controlled environment horticulture: Indoor farming and its key technologies. *HortScience* **2022**, *57*, 247–256. [CrossRef]
175. Armanda, D.T.; Guinée, J.B.; Tukker, A. The second green revolution: Innovative urban agriculture's contribution to food security and sustainability—A review. *Glob. Food Sec.* **2019**, *22*, 13–24. [CrossRef]
176. Hardy, K.; Orridge, T.; Heynes, X.; Gunasena, S.; Grundy, S.; Lu, C. Farming the future: Contemporary innovations enhancing sustainability in the agri-sector. *Annu. Plant Rev.* **2021**, *4*, 263–294. [CrossRef]
177. Piechowiak, M. Countries Using Vertical Farming, Vertical Farming Planet. Available online: https://verticalfarmingplanet.com/countries-using-vertical-farming/#:~:text=There%20are%20currently%20over%20200,that%20focus%20on%20producing%20vegetables (accessed on 2 September 2023).
178. Takeshima, H.; Joshi, P.K. Protected Agriculture, Precision Agriculture, and Vertical Farming: Brief Reviews of Issues in the Literature Focusing on the Developing Region in Asia. 2019. Available online: https://www.ifpri.org/publication/protected-agriculture-precision-agriculture-and-vertical-farming-brief-reviews-issues (accessed on 2 September 2023).
179. Kalantari, F.; Tahir, O.M.; Joni, R.A.; Fatemi, E. Opportunities and challenges in sustainability of vertical farming: A review. *J. Landsc. Ecol.* **2018**, *11*, 35–60. [CrossRef]
180. Takada, A. As High-Rise Farms Go Global, Japan's Spread Leads the Way. Available online: https://www.japantimes.co.jp/news/2018/11/01/business/tech/high-rise-farms-go-global-japans-spread-leads-way/ (accessed on 28 January 2023).
181. Wen, X. Vertical Farming Reaches New Heights. 13 April 2023. Available online: https://www.chinadaily.com.cn/a/202304/13/WS64373a55a31057c47ebb9cb0_3.html (accessed on 20 February 2023).
182. Yan, X. Chinese Startup Gets in on Ground Floor of High-Rise Farms. 17 August 2020. Available online: https://asia.nikkei.com/Business/Startups/Chinese-startup-gets-in-on-ground-floor-of-high-rise-farms (accessed on 20 February 2023).
183. Ning, S.; Xydis, G. PEST analysis of the future Chinese vertical farming market: Environmental sustainability and energy savings. *AIMS Agric. Food* **2023**, *8*, 496–512. [CrossRef]
184. Chatterjee, A.; Debnath, S.; Pal, H. Implication of urban agriculture and vertical farming for future sustainability. In *Urban Horticulture*; Solankey, S.S., Ed.; IntechOpen: Rijeka, Croatia, 2020; pp. 1–11. [CrossRef]
185. Kollenberg, K.A. Vertical Farming; Can Urban Agriculture Feed a Hungry World? 22 July 2011. Available online: https://cityfarmer.info/south-korean-city-of-suwon-has-a-vertical-farm/ (accessed on 22 December 2022).
186. John. The Rise of Smart Vertical Farms in Korea—The Future of Farming. 25 May 2022. Available online: https://www.seoulz.com/the-rise-of-smart-vertical-farms-in-korea-the-future-of-farming/ (accessed on 5 January 2023).
187. NextOn. Available online: http://nexton.ag/about/index.php (accessed on 10 February 2023).
188. Farm8. Available online: http://en.farm8.co.kr/ (accessed on 10 February 2023).
189. N.Thing. Available online: https://nthing.net/TECH (accessed on 10 February 2023).
190. ALGA Farmtech. Available online: http://en.algafarmtech.com/index (accessed on 10 February 2023).
191. Mordor Intelligence. Vertical Farming Market Size & Share Analysis-Growth Trends & Forecasts (2023–2028). Available online: https://www.mordorintelligence.com/industry-reports/vertical-farming-market (accessed on 2 April 2023).
192. 80 Acres Farms. Available online: https://www.80acresfarms.com/ (accessed on 12 April 2023).

193. Kozai, T.; Niu, G. Selected PFALs in the United States, the Netherlands, and China. In *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*, 2nd ed.; Kozai, T., Niu, G., Takagaki, M., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 419–436. [CrossRef]
194. American Hydroponics. Available online: https://amhy-dro.com/ (accessed on 31 May 2023).
195. Bright Farms. Available online: https://www.brightfarms.com/ (accessed on 31 May 2023).
196. Hort Americas. Available online: https://hortameri-cas.com/ (accessed on 31 May 2023).
197. The Plant. Available online: https://www.insidetheplant.com/ (accessed on 31 May 2023).
198. FarmedHere. Available online: http://www.farmedhere.com/ (accessed on 31 May 2023).
199. 80 Acres Farms Layoffs Linked to Industry & Other Collapses. Available online: :https://igrownews.com/80-acres-farms-layoffs-linked-to-industry-other-collapses/ (accessed on 31 May 2023).
200. den Besten, J. Vertical farming development; the Dutch approach. In *Plant Factory Using Artificial Light*; Anpo, M., Fukuda, H., Wada, T., Eds.; Elsevier: Cambridge, MA, USA, 2019; pp. 307–317. [CrossRef]
201. Benis, K.; Ferrão, P. Commercial farming within the urban built environment–Taking stock of an evolving field in northern countries. *Glob. Food Sec.* **2018**, *17*, 30–37. [CrossRef]
202. PlantLab. Available online: https://plantlab.com/ (accessed on 15 April 2023).
203. UrbanFarmers. Available online: http://www.urbanfarmers.nl/ (accessed on 15 April 2023).
204. B-Four Agro. Available online: https://b4agro.nl/ (accessed on 15 April 2023).
205. Agricool. Available online: https://www.agritec-tu-re.com/agricool/ (accessed on 2 June 2023).
206. Infarm. Available online: https://www.infarm.com/ (accessed on 2 June 2023).
207. Farmers Cut. Available online: https://farmerscut.com/ (accessed on 2 June 2023).
208. Architects, S. A New Model for Urban Farming for the World's Largest Agricultural Producer and Consumer: China, Sunqiao Urban Agricultural District. Available online: https://www.sasaki.com/projects/sunqiao-urban-agricultural-district/ (accessed on 12 July 2023).
209. La Tour Vivante—The Living Tower. SOA Architectes. Available online: https://archello.com/project/la-tour-vivante-the-living-tower (accessed on 10 June 2023).
210. Jian Mu Tower. Farmscraper—Tall Building Design Meets Urban Farming. 2021. Available online: https://carloratti.com/project/jian-mu-tower/ (accessed on 9 May 2023).
211. Jordana, S. Harvest Green Project/Romses Architects. ArchDaily. 7 May 2009. Available online: https://www.archdaily.com/21555/harvest-green-project-romses-architects (accessed on 18 June 2023).
212. Romses Architects. Harvest Green Tower. Available online: http://www.romsesarchitects.com/harvest_green.html (accessed on 18 June 2023).
213. Urban Skyfarm. Available online: http://www.aprilli.com/urban-skyfarm/ (accessed on 12 April 2023).
214. Peters, A. This Tree-Shaped Farm-On-A-Skyscraper Could Bring Acres of Crops into the City. Available online: https://www.fastcompany.com/3032379/this-tree-shaped-farm-on-a-skyscraper-could-bring-acres-of-crops-into-the-city (accessed on 12 April 2023).
215. Spread Co., Ltd. Largest FoodTech Deal in Japan: Vertical Farming Startup Spread Raises $30 Million to Accelerate Its Business. 2 August 2022. Available online: https://spread.co.jp/uploads/news-release_20220802-1.pdf (accessed on 22 May 2023).
216. Hive-Inn^{TM} City Farm. New York, NY, USA. Available online: https://www.ovastudio.com/work/hive-inn-city-farm-nyc (accessed on 12 December 2022).
217. Markham, D. Repurposed Shipping Containers May Be Building Blocks for Modular Vertical Urban Farms. Treehugger News. 11 October 2018. Available online: https://www.treehugger.com/shipping-container-repurposed-vertical-urban-farm-4855558 (accessed on 12 December 2022).
218. Orsini, F.; Pennisi, G.; Zulfiqar, F.; Gianquinto, G. Sustainable use of resources in plant factories with artificial lighting (PFALs). *Eur. J. Hortic. Sci.* **2020**, *85*, 297–309. [CrossRef]
219. Roberts, J.M.; Bruce, T.J.A.; Monaghan, J.M.; Pope, T.W.; Leather, S.R.; Beacham, A.M. Vertical farming systems bring new considerations for pest and disease management. *Ann. Appl. Biol.* **2020**, *176*, 226–232. [CrossRef]
220. Hegedűs, C.; Frankó, A.; Varga, P.; Gindl, S.; Tauber, M. Enabling Scalable Smart Vertical Farming with IoT and Machine Learning Technologies. In Proceedings of the NOMS 2023—2023 IEEE/IFIP Network Operations and Management Symposium, Miami, FL, USA, 8–12 May 2023; pp. 1–4. [CrossRef]
221. Mempel, H.; Jüttner, I.; Wittmann, S. The potentials of indoor farming for plant production. *Automatisierungstechnik* **2021**, *69*, 287–296. [CrossRef]
222. Zhu, X.-G.; Marcelis, L. Vertical farming for crop production. *Mod. Agric.* **2023**, *1*, 13–15. [CrossRef]
223. Naqvi, S.M.Z.A.; Saleem, S.R.; Tahir, M.N.; Hussain, S.; Ul Haq, S.I.; Awais, M.; Qamar, S. Vertical Farming-Current Practices and Its Future. *Environ. Sci. Proc.* **2022**, *23*, 4. [CrossRef]
224. Sarkar, A.; Majumder, M. Opportunities and challenges in sustainability of vertical eco-farming: A review. *J. Adv. Agric. Technol.* **2015**, *2*, 98–105. [CrossRef]
225. Abdullah, M.J.; Zhang, Z.; Matsubae, K. Potential for food self-sufficiency improvements through indoor and vertical farming in the gulf cooperation council: Challenges and opportunities from the case of Kuwait. *Sustainability* **2021**, *13*, 12553. [CrossRef]
226. Csordás, A.; Füzesi, I. The impact of technophobia on vertical farms. *Sustainability* **2023**, *15*, 7476. [CrossRef]

227. Siregar, R.R.A.; Seminar, K.B.; Wahjuni, S.; Santosa, E. Vertical farming perspectives in support of precision agriculture using artificial intelligence: A review. *Computers* **2022**, *11*, 135. [CrossRef]
228. Kim, H.-G.; Park, D.-H.; Chowdhury, O.R.; Shin, C.-S.; Cho, Y.-Y.; Park, J.-W. Location-based intelligent robot management service model using RGPSi with AoA for vertical farm. *Lect. Notes Electr. Eng.* **2014**, *279*, 309–314. [CrossRef]
229. Swain, M. Vertical farming trends and challenges: A new age of agriculture using IoT and machine learning. In *Internet of Things for Agriculture 4.0: Impact and Challenges*; Sing, R.S., Thakur, A.K., Gehlot, A., Kaviti, A.K., Eds.; Academic Press: Boca Raton, FL, USA, 2022; pp. 1–16.
230. Shrivastava, A.; Nayak, C.K.; Dilip, R.; Samal, S.R.; Rout, S.; Ashfaque, S.M. Automatic robotic system design and development for vertical hydroponic farming using IoT and big data analysis. *Mater. Today Proc.* **2023**, *80*, 3546–3553. [CrossRef]
231. Larsen, D.H.; Woltering, E.J.; Nicole, C.C.S.; Marcelis, L.F.M. Response of basil growth and morphology to light intensity and spectrum in a vertical farm. *Front. Plant Sci.* **2020**, *11*, 597906. [CrossRef] [PubMed]
232. Lehnert, C.; McCool, C.; Sa, I.; Perez, T. Performance improvements of a sweet pepper harvesting robot in protected cropping environments. *J. Field Robot.* **2020**, *37*, 1197–1223. [CrossRef]