Technological Trends and Engineering Issues on Vertical Farms

Subjects: Agricultural Engineering

Contributor: Md Shaha Nur Kabir, Md Nasim Reza, Milon Chowdhury, Mohammod Ali, Samsuzzaman Samsuzzaman, Md Razob Ali, Ka Young Lee, Sun-Ok Chung

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. 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.

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

1. Introduction

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 [1][2]. 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 [2][3][4]. 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][6]. 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. Vertical farming optimizes space, reducing the need for land and construction in cities, with a growing demand fueled by the popularity of organic food [7]. 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.

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 [8][9]. 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 [10]. 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 [11]. This trend is particularly promising for enhancing food sustainability in urban areas and presents opportunities to positively impact the environment, society, and economy [12][13]. 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.

2. Vertical Farming

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 [14]. They are a modern approach to agriculture [15] that addresses challenges in food production due to population growth, environmental concerns, and limited space [11], enabling efficient cultivation of various products in controlled environments for increased yield [16][17].

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 [14][18]. Other indoor-farming concepts, such as high-density vertical growing (HDVG) [11][19], which falls under CEA, and the widely recognized plant factories (PFs), including plant factories with artificial lighting (PFALs) [20] and plant production systems with artificial lighting (PPALs) [21], 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) [18]. A less common term, sky farming, pertains to agriculture in high-rise buildings [11]. Waldron [22] 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 1**).

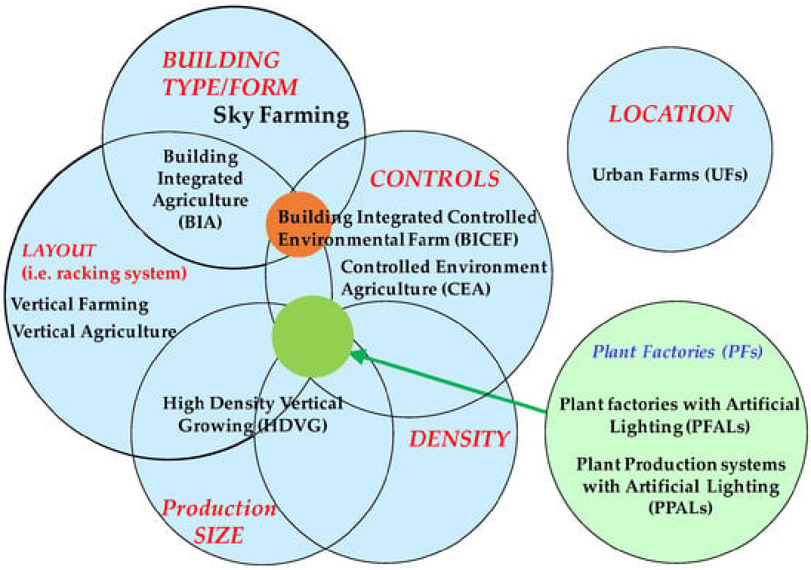

Figure 1. Types of vertical farms and influencing factors (adapted from [22]).

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 [23]. 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) [24].

Vertical farming encompasses categories like PFALs, container farms, in-store farms, and appliance farms [9][23]. 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 [9][17][25][26].

Figure 2 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 [9][17][27]. 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.

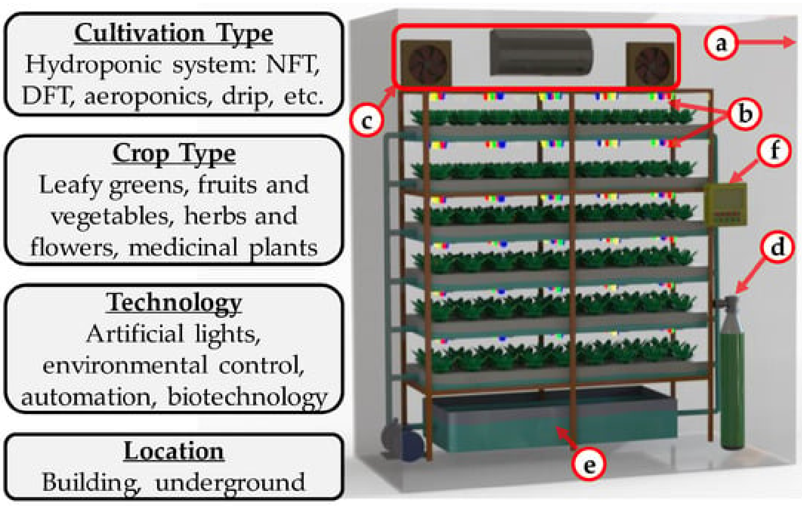

Figure 2. Configuration of a vertical farm: (**a**) thermally well-insulated and tightly sealed walls; (**b**) multilevel structure with lighting equipment; (**c**) air conditioner with fan; (**d**) CO_2 supply unit; (**e**) hydroponic system (nutrient-solution supply unit); and (**f**) environmental control unit. (adapted from [17][28][29]).

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 [29].

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 [30]. 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 3**.

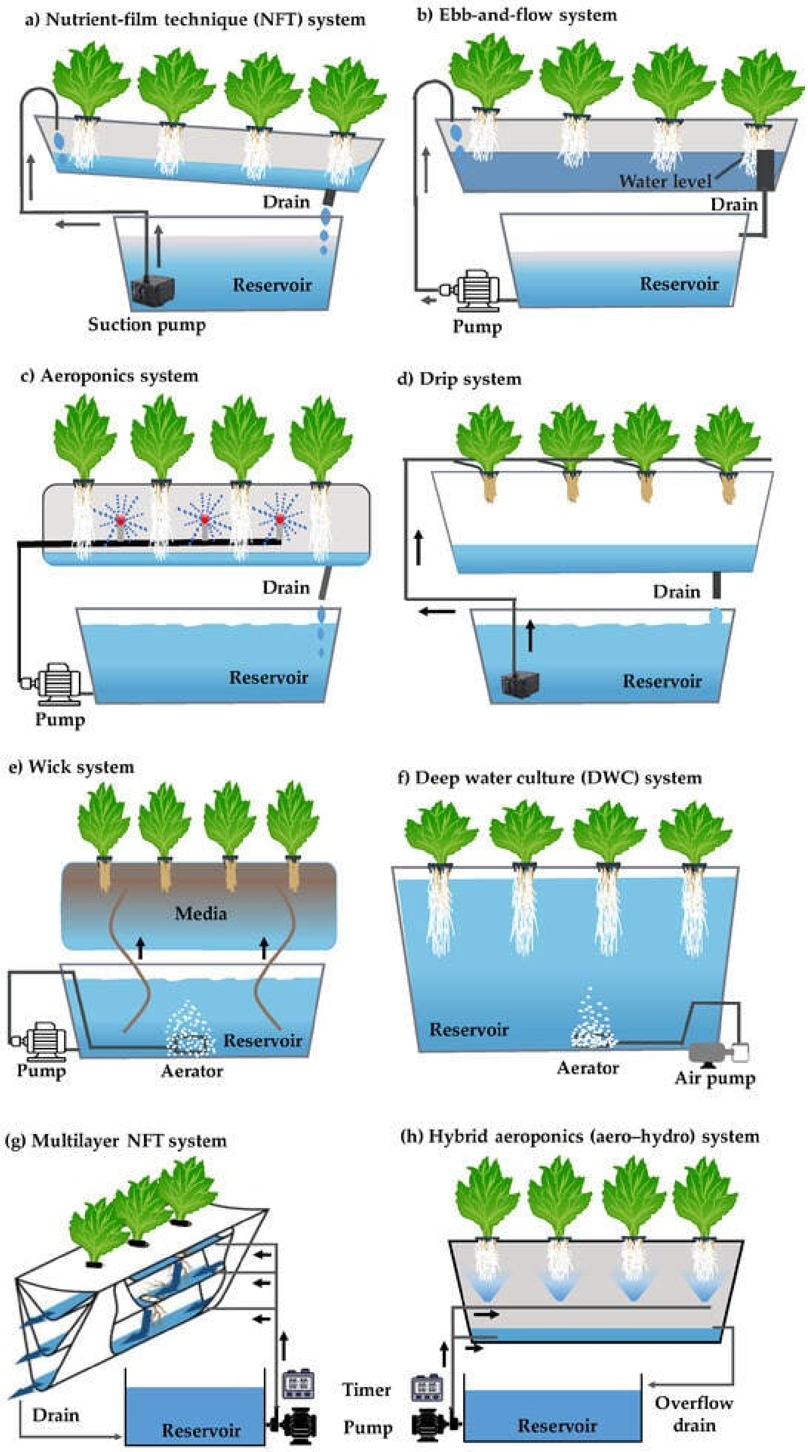

Figure 3. Schematic diagrams of hydroponic systems: (**a**) nutrient-film technique (NFT); (**b**) ebb-and-flow technique; (**c**) aeroponics; (**d**) drip; (**e**) wick; (**f**) deep water culture (DWC); (**g**) multilayer NFT; (**h**) hybrid aeroponics (aero–hydro). Adapted from [30][31][32][33].

Aeroponics, a variation of hydroponics, involves misting plant roots with air or a water solution regularly [34], 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.

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.

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 [35][36][37]. 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 [38][39][40].

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 [41]. 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.

An advanced cylindrical hydroponics system employing the revoponics technique has been developed [42]. 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 [43].

The Radix hydroponic module [44] 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.

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 [11][20].

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].

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 [29].

Lighting plays a critical role in the cultivation of crops on vertical farms, particularly artificial lighting such as LEDs, which replace natural sunlight [6]. 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 [45][46]. 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 [10].

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 [31].

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 [29]. 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 [12].

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 [47]. 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 [48]. They reduce the need for constant human intervention by interfacing with environmental variables and capturing critical data, such as light, temperature, and pH changes [49]. 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 [50].

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 [51].

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 [52]. 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 [49]. 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 [53].

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 [49][50]. 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.

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 [54]. 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 [55].

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 [56][57][58][59].

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 [60]. Continued recycling of drainage water may result in the buildup of specific nutrients like calcium, causing changes in nutrient proportions [61]. 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 4** illustrates several hydroponic nutrient-monitoring techniques.

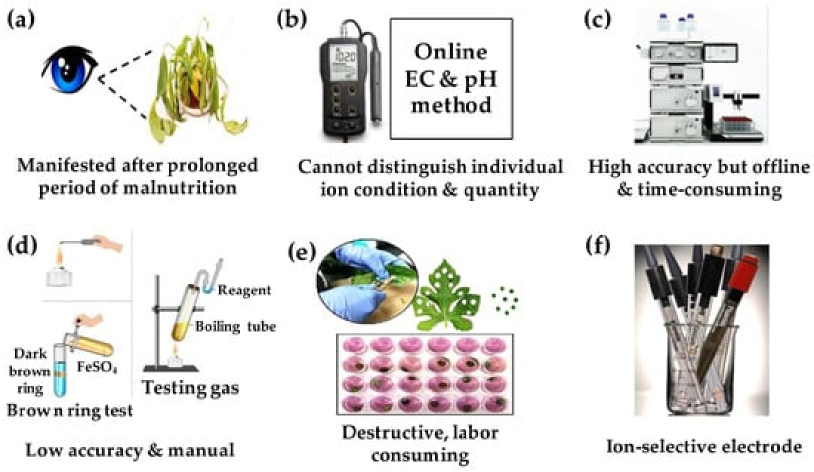

Figure 4. Hydroponic nutrient monitoring techniques include (**a**) visual assessment of plant symptoms; (**b**) electrical conductivity (EC) and pH assessment; (**c**) laboratory analysis using an ion chromatography machine; (**d**) manual salt testing; (**e**) leaf tissue analysis; and (**f**) ion-specific nutrient analysis using ion-selective electrodes.

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 [62][63]. This cutting-edge approach utilizes IoT-enabled devices to continuously monitor and control the crop-growing environment, enhancing food production with limited resources [64][65]. 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 [66][67].

Growers can customize the environments for different crops through IoT-enabled devices, confirming standard growth conditions for individual plants remotely [68][69]. 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.

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 [70][71][72]. 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 [49]. 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 5**.

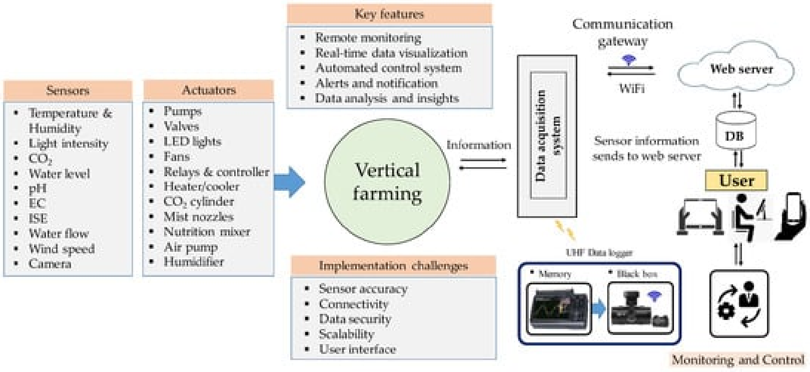

Figure 5. Schematic representation of IoT-based monitoring and control systems for vertical farms.

Visual sensor technology revolutionizes vertical farming by enabling comprehensive crop growth monitoring through image-based analysis [31][73][74]. 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 [75]. These data aid in the early detection of issues and facilitate timely interventions.

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 [76]. Chlorophyll-fluorescence sensors analyze photosynthetic activity, indicating plant stress levels [77]. Spectral sensors measure light absorption and reflection, aiding in the detection of nutrient deficiency [78]. Optical sensors also contribute to light management, with quantum sensors measuring available light for photosynthesis, enabling farmers to adjust artificial lighting setups [79]. Additionally, multispectral sensors can assess plant health through changes in color and reflectance. These technologies enhance precision and efficiency in vertical farming [80].

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 [81]. 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 [49].

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 [82]. Unmanned vertical farming systems are not constrained by seasonal changes or adverse weather conditions, enabling year-round crop production, which contributes to food security [49].

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 [31][83]. 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 [84]. 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 [85]. 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 [86].

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 [87] cuts labor by 30% and energy by 33%. Around 28.4% of vertical farms use IT-driven automation, with more adoption planned [88]. 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.

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 [82], 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 [31].

Avgoustaki et al. [82] 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 [89] 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 [90] 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 [23].

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.

iFarm [91] is effectively experimenting with computer vision technology to enable the monitoring of plant-growth stages on vertical farms using UAVs. 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 [92]. Corvus Drones [93] 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.

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 [94]. The success of vertical farming is intricately tied to technology, with automation and AI at the forefront of transformative innovations in food cultivation [95]. 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 [94]. 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 [96].

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 [66]. 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 [73].

To assess leaf stress levels, Story et al. [97] 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. [98] developed a multiscale hierarchical convolutional neural network (MFC-CNN) architecture and evaluated its performance across different stress levels.

Utilizing advanced deep-learning techniques, Wu et al. [99] 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. [100] 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.

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 [101]. 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 [102].

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 [103]. Unlike traditional methods, vertical farming involves monitoring and controlling all aspects, including artificial lighting, to maximize space efficiency [10][104]. 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 [105]. 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 [19].

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 [106]. 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.

In China, there are approximately 250 active vertical farming sites, and the number is steadily rising [107]. 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 [108]. 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 [105]. 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 [109]

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 [110]. 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 [110].

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 [111]. 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 [112]. 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 [23].

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 [23].

Sasaki Architects [113] 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 [103] 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.

5. 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 6** provides a concise overview of the prospects and challenges associated with vertical farming in sustainable food production.

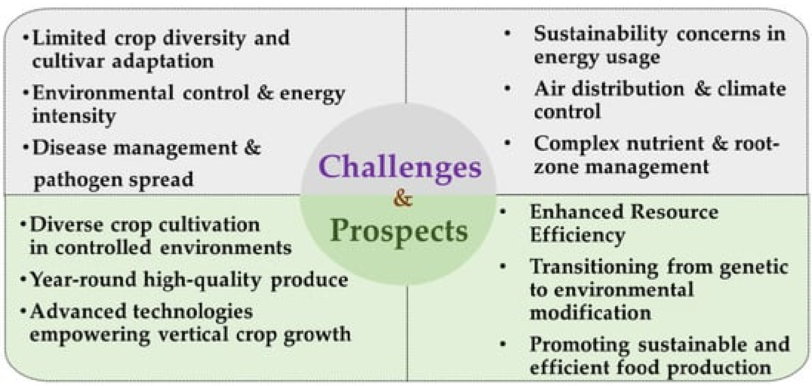

Figure 6. Prospects and challenges of sustainable food production in an urban area.

References

1. Ragaveena, S.; Shirly Edward, A.; Surendran, U. Smart controlled environment agriculture methods: A holistic review. Rev. Environ. Sci. Biotechnol. 2021, 20, 887–913.
2. Gan, C.I.; Soukoutou, R.; Conroy, D.M. Sustainability framing of controlled environment agriculture and consumer perceptions: A review. Sustainability 2023, 15, 304.
3. Engler, N.; Krarti, M. Review of energy efficiency in controlled environment agriculture. Renew. Sustain. Energy Rev. 2021, 141, 110786.
4. 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.
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.
6. 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.
7. 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).
8. 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.
9. 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.
10. 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.
11. 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.
12. Al-Kodmany, K. The Vertical Farm: A review of developments and implications for the vertical city. Buildings 2018, 8, 24.
13. 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.
14. 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.
15. 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.
16. Banerjee, C.; Adenaeuer, L. Up, up and away! The economics of vertical farming. J. Agric. Stud. 2014, 2, 40–60.
17. Van Gerrewey, T.; Boon, N.; Geelen, D. Vertical Farming: The only way is up? Agronomy 2022, 12, 2.
18. 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.
19. 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.
20. 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.
21. 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.
22. Waldron, D. Evolution of vertical farms and the development of a simulation methodology. WIT Trans. Ecol. Environ. 2018, 217, 975–986.

23. 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.

24. SharathKumar, M.; Heuvelink, E.; Marcelis, L.F.M. Vertical farming: Moving from genetic to environmental modification. Trends Plant Sci. 2020, 25, 724–727.

25. 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).

26. 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.

27. 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.

28. 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.

29. 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.

30. 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.

31. 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.

32. 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.

33. 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.

34. 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.

35. Aerofarms. Available online: https://aerofarms.com/ (accessed on 26 August 2023).

36. Plenty. Available online: https://www.plenty.ag/ (accessed on 26 August 2023).

37. Bowery. Available online: https://bowery.co/ (accessed on 26 August 2023).

38. 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.

39. 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.

40. 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.

41. NGS. New Growing System. Available online: https://ngsystem.com (accessed on 8 April 2023).

42. Omega Garden™. Hydroponics Design. Available online: https://omegagarden.com/ (accessed on 10 July 2023).

43. Farmdominium™. The Farmdominium™ Concept. Available online: https://omegagarden.com/the-farmdominium/ (accessed on 10 July 2023).

44. 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).

45. Pocock, T. Light-emitting diodes and the modulation of specialty crops: Light sensing and signaling networks in plants. HortScience 2015, 50, 1281–1284.

46. Pattison, P.; Tsao, J.; Brainard, G.; Bugbee, B. LEDs for photons, physiology and food. Nature 2018, 563, 493–500.

47. 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.
48. Singh, N.; Singh, A.N. Odysseys of agriculture sensors: Current challenges and forthcoming prospects. Comput. Electron. Agric. 2020, 171, 105328.
49. 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.
50. 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.
51. 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.
52. 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.
53. 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.
54. 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.
55. 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.
56. 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.
57. 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.
58. 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.
59. 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.
60. Asaduzzaman, M.; Asao, T. Autotoxicity in strawberry under recycled hydroponics and its mitigation methods. Hortic. J. 2020, 89, 124–137.
61. 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.
62. Dhanaraju, M.; Chenniappan, P.; Ramalingam, K.; Pazhanivelan, S.; Kaliaperumal, R. Smart farming: Internet of things (IoT)-based sustainable agriculture. Agriculture 2022, 12, 1745.
63. Crisnapati, P.N.; Wardana, I.N.K.; Aryanto, I.K.A.A.; Hermawan, A. Hommons: Hydroponic management and monitoring 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.
64. 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.
65. 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.
66. 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.
67. 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.
68. 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.
69. 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.

70. 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.

71. 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.

72. 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.

73. 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.

74. 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.

75. 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.

76. 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.

77. Pérez-Bueno, M.L.; Pineda, M.; Barón, M. Phenotyping plant responses to biotic stress by chlorophyll fluorescence imaging. Front. Plant Sci. 2019, 10, 1135.

78. 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.

79. Brzychczyk, B.; Hebda, T.; Fitas, J.; Giełżecki, J. The follow-up photobioreactor illumination system for the cultivation of photosynthetic microorganisms. Energies 2020, 13, 1143.

80. 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.

81. 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.

82. 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.

83. 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.

84. 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).

85. CityCrop. Automated Indoor Farming. Available online: https://citycrop.io/ (accessed on 13 February 2023).

86. 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).

87. iFarm. iFarm StackGrow Vertical Farming Automation Technology. Available online: https://ifarm.fi/technologies/stack-grow (accessed on 16 July 2023).

88. 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).

89. 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).

90. 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).

91. iFarm. Available online: https://ifarm.fi/ (accessed on 2 March 2023).

92. iFarm. Autonomous Drones Will Help to Observe Plants. Available online: https://ifarm.fi/dron_on_farm (accessed on 18 August 2023).

93. Corvus Drones. Available online: https://www.corvusdrones.com/ (accessed on 20 May 2023).

94. 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).

95. 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.

96. 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.

97. 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.

98. 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.

99. 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.

100. 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.

101. Avgoustaki, D.D.; Xydis, G. Indoor vertical farming in the urban nexus context: Business growth and resource savings. Sustainability 2020, 12, 1965.

102. Mitchell, C.A. History of controlled environment horticulture: Indoor farming and its key technologies. HortScience 2022, 57, 247–256.

103. 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).

104. 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.

105. 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.

106. 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).

107. 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).

108. 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).

109. 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.

110. 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).

111. 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.

112. 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.

113. 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).