Vertical Farming: Addressing the Challenges of 21st Century Agriculture Through Innovation

Abstract

Vertical farming has emerged as a promising solution to address the challenges faced by 21st century agriculture. As the global population continues to grow and urbanization increases, traditional agricultural practices are struggling to meet the rising demand for food while also grappling with issues such as climate change, resource scarcity, and environmental degradation. Vertical farming offers a sustainable and efficient alternative by leveraging innovative technologies and controlled environments to grow crops in vertically stacked layers within urban settings. This article explores the concept of vertical farming, its advantages, and the challenges associated with its implementation. It delves into the various technologies and systems employed in vertical farms, including hydroponics, aeroponics, and aquaponics, and discusses their potential to optimize resource utilization and enhance crop yields. The article also examines the economic viability and social implications of vertical farming, highlighting its potential to create jobs, reduce food miles, and improve food security in urban areas. Furthermore, it addresses the challenges and limitations of vertical farming, such as high initial costs, energy requirements, and the need for specialized skills. The article concludes by emphasizing the importance of further research, investment, and collaboration to scale up vertical farming and harness its full potential in shaping the future of sustainable agriculture.

Keywords: Vertical Farming, Sustainable Agriculture, Urban Agriculture, Controlled Environment Agriculture, Hydroponics, Aeroponics, Aquaponics

1. Introduction

1.1 Background

Vertical farming has emerged as a promising solution to address the pressing challenges faced by traditional agriculture in the 21st century. As the global population continues to grow at an unprecedented rate, reaching an estimated 9.7 billion by 2050 [1], the demand for food production is expected to increase by 70% [2]. Simultaneously, rapid urbanization has led to the expansion of cities, reducing the availability of arable land for agricultural purposes. Climate change, environmental degradation, and resource scarcity further exacerbate the situation, making it imperative to explore innovative and sustainable farming practices.

Vertical farming offers a potential answer to these challenges by revolutionizing the way crops are cultivated. By leveraging advanced technologies and controlled environments, vertical farms enable the production of crops in vertically stacked layers within enclosed structures, optimizing land use and resource efficiency [3]. This approach not only increases crop yields but also reduces the environmental impact associated with traditional farming methods, such as water consumption, pesticide use, and carbon emissions [4]. The concept of vertical farming has gained significant attention in recent years, with numerous pilot projects and commercial ventures being established worldwide. From small-scale urban farms to large-scale industrial facilities, vertical farming has demonstrated its potential to contribute to food security, urban sustainability, and the development of resilient food systems [5].

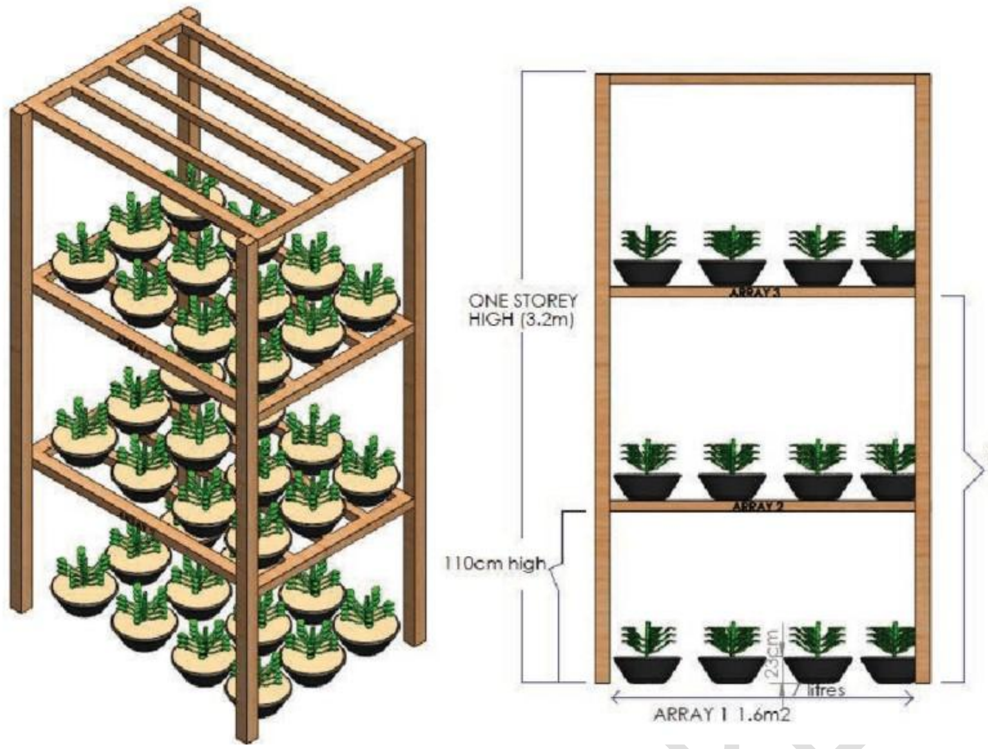

Figure 1: Schematic representation of a vertical farming system

1.2 Objectives

The primary objective of this article is to provide a comprehensive overview of vertical farming and its role in addressing the challenges of 21st-century agriculture. The article aims to:

1. Explore the concept of vertical farming, its principles, and its evolution over time.
2. Discuss the advantages and benefits of vertical farming compared to traditional agricultural practices.
3. Examine the various technologies and systems employed in vertical farms, including hydroponics, aeroponics, and aquaponics.
4. Analyze the economic viability and business models associated with vertical farming.
5. Assess the social and environmental impact of vertical farming, including its potential to enhance food security, create jobs, and mitigate climate change.
6. Identify the challenges and limitations faced by vertical farming and propose strategies to overcome them.
7. Highlight future prospects and research directions in the field of vertical farming.

By addressing these objectives, the article seeks to provide a holistic understanding of vertical farming and its potential to revolutionize sustainable agriculture in the 21st century.

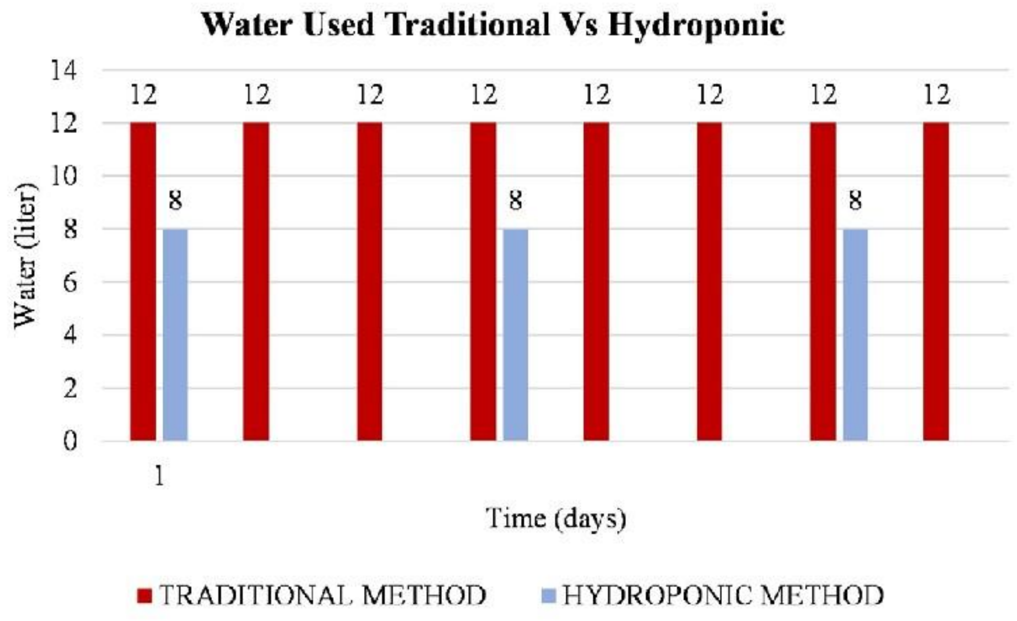

Figure 2: Comparison of crop yields in vertical farming and traditional agriculture

Table 1: Comparison of Traditional Agriculture and Vertical Farming

Characteristic	**Traditional Agriculture**	**Vertical Farming**
Land Use	Extensive	Intensive
Water Consumption	High	Low
Pesticide Use	Common	Minimal
Crop Yield	Moderate	High
Labor Requirement	High	Moderate
Energy Efficiency	Low	High
Weather Dependency	High	Low
Transportation Costs	High	Low
Carbon Footprint	High	Low
Urban Accessibility	Low	High

Table 2: Advantages and Disadvantages of Hydroponics, Aeroponics, and Aquaponics

System	**Advantages**	**Disadvantages**
Hydroponics	- Efficient water and nutrient use - High crop yields - Precise control over nutrient	- Requires specialized knowledge and equipment - Dependence on electricity and pumps

	delivery - Suitable for a wide range of crops	- Risk of waterborne diseases - Limited root space
Aeroponics	- Minimal water and nutrient use - Excellent aeration for roots - Reduced risk of plant diseases - Faster growth rates	- High initial setup costs - Requires precise control and monitoring - Vulnerable to power outages - Limited to certain crop types
Aquaponics	- Sustainable and eco-friendly - Nutrient-rich water from fish waste - Reduced need for fertilizers - Dual production of fish and crops	- Complex system design and management - Balancing nutrient levels for fish and plants - Higher initial costs and maintenance - Limited fish species suitable for the system

1.3 Scope

The scope of this article encompasses the various aspects of vertical farming, from its conceptual foundations to its practical applications. The article will explore the historical context and evolution of vertical farming, tracing its development from early conceptual ideas to modern-day implementations.

The article will delve into the technical aspects of vertical farming, discussing the different technologies and systems employed, such as hydroponics, aeroponics, and aquaponics. It will also examine the role of controlled environment agriculture (CEA) in vertical farming, including environmental control systems, automation, and monitoring techniques.

The economic dimensions of vertical farming will be analyzed, including investment requirements, operating costs, market demand, and profitability. The article will explore different business models and strategies for scalability and expansion.

The social and environmental implications of vertical farming will be discussed, highlighting its potential to address food security, urban sustainability, and job creation. The article will also examine the challenges and limitations associated with vertical farming, such as high initial costs, energy requirements, and the need for skilled labor.

Finally, the article will explore future prospects and research directions in vertical farming, discussing potential technological advancements, policy support, and collaborative efforts needed to scale up and mainstream vertical farming practices. By covering these diverse aspects, the article aims to provide a comprehensive understanding of vertical farming and its role in shaping the future of sustainable agriculture.

2. Challenges of 21st Century Agriculture

2.1 Population Growth and Urbanization

One of the most significant challenges facing agriculture in the 21st century is the rapid growth of the global population. The United Nations projects that the world population will reach 9.7 billion by 2050, with the majority of this growth occurring in developing countries [1]. This population increase, coupled with the trend of urbanization, puts immense pressure on the agricultural sector to meet the rising demand for food. As more people migrate to cities, the availability of arable land for farming decreases, making it necessary to find innovative solutions to produce food in urban settings [6].

2.2 Climate Change and Environmental Degradation

Climate change and environmental degradation pose significant threats to agriculture in the 21st century. Rising temperatures, changes in precipitation patterns, and increased frequency of extreme weather events, such as droughts and floods, can have detrimental effects on crop yields and quality

[7]. Agriculture itself contributes to environmental degradation through practices such as deforestation, excessive water consumption, and the use of chemical fertilizers and pesticides. These practices lead to soil erosion, biodiversity loss, and greenhouse gas emissions, further exacerbating the challenges faced by the agricultural sector [8].

2.3 Resource Scarcity and Land Limitations

Resource scarcity, particularly in terms of water and land, is another major challenge for agriculture. Agriculture accounts for approximately 70% of global freshwater withdrawals, putting a strain on already limited water resources [9]. With the increasing demand for food production, the competition for water between agriculture, industry, and human consumption is expected to intensify. Additionally, the availability of arable land is limited, and the expansion of agricultural land often comes at the cost of deforestation and habitat destruction. Urbanization and land degradation further reduce the amount of suitable land for farming, necessitating the development of resource-efficient and space-saving agricultural practices [10].

2.4 Food Security and Accessibility

Ensuring food security and accessibility is a critical challenge in the 21st century. Despite advancements in agricultural productivity, millions of people worldwide still suffer from hunger and malnutrition. Factors such as poverty, inequality, and food waste contribute to this issue [11]. Moreover, the uneven distribution of food production and the long distances food travels from farm to plate can lead to food deserts in urban areas, where access to fresh and nutritious produce is limited [12]. Addressing food security and accessibility requires not only increasing food production but also improving food distribution systems and ensuring affordable access to healthy food for all.

Table 3: Comparison of Lighting Systems in Vertical Farming

Lighting System	**Efficiency**	**Lifespan**	**Spectrum Control**	**Heat Emission**
Fluorescent Lights	Moderate	Moderate	Limited	Moderate
High-Pressure Sodium (HPS) Lights	High	Long	Limited	High
Metal Halide (MH) Lights	High	Moderate	Limited	High
Light Emitting Diodes (LEDs)	Very High	Very Long	Excellent	Low

Table 4: Suitable Crops for Vertical Farming

Crop Category	**Examples**
Leafy Greens	Lettuce, Spinach, Kale, Arugula, Swiss Chard
Herbs	Basil, Mint, Cilantro, Parsley, Rosemary
Microgreens	Radish, Broccoli, Sunflower, Pea Shoots, Wheatgrass

Fruiting Crops	Tomatoes, Peppers, Cucumbers, Strawberries, Eggplants
Root Crops	Carrots, Radishes, Beets, Turnips, Potatoes

Table 5: Water-Saving Techniques in Vertical Farming

Technique	**Description**	**Water Savings**
Drip Irrigation	Precise delivery of water directly to plant roots	Up to 70%
Hydroponic Systems	Recirculating water with dissolved nutrients	Up to 90%
Aeroponic Systems	Misting plant roots with nutrient-rich water	Up to 95%
Moisture Sensors	Monitoring soil moisture levels for optimized irrigation	Up to 40%
Rainwater Harvesting	Collecting and storing rainwater for irrigation	Varies

3. Vertical Farming: Concept and Overview

3.1 Definition and Principles

Vertical farming is an innovative approach to agriculture that involves growing crops in vertically stacked layers within controlled environments, such as buildings or warehouses [3]. The primary principle of vertical farming is to maximize crop production per unit area by utilizing vertical space and optimizing growing conditions. By employing advanced technologies and controlled environment agriculture (CEA) techniques, vertical farms aim to provide a sustainable and efficient alternative to traditional land-based farming [13].

3.2 History and Evolution

The concept of vertical farming can be traced back to the early 20th century, with visionary ideas proposed by architects and scientists. In 1915, American geologist Gilbert Ellis Bailey coined the term "vertical farming" and envisioned tall structures with multiple levels for crop cultivation [14]. However, it was not until the late 20th and early 21st centuries that advances in technology and the pressing need for sustainable agriculture brought vertical farming to the forefront. The modern concept of vertical farming gained prominence with the work of Dickson Despommier, a professor at Columbia University, who popularized the idea through his book "The Vertical Farm: Feeding the World in the 21st Century" [1].

3.3 Advantages and Benefits

Vertical farming offers numerous advantages and benefits compared to traditional agricultural practices. One of the primary advantages is the ability to produce crops year-round, independent of seasonal weather conditions, by controlling the indoor environment [15]. Vertical farms also require significantly less water, as hydroponic and aeroponic systems enable the recirculation and reuse of water, reducing water consumption by up to 95% compared to conventional farming [16]. The controlled environment of vertical farms minimizes the need for pesticides and herbicides, resulting in safer and healthier produce [17].

Moreover, vertical farming allows for the localization of food production, reducing the distance food travels from farm to consumer and minimizing food miles and associated carbon emissions [18]. By bringing agriculture closer to urban centers, vertical farming can contribute to food security and improve access to fresh produce in urban food deserts [19]. Vertical farms also have the potential to create green jobs and foster sustainable urban development, contributing to the social and economic well-being of communities [20].

4. Technologies and Systems in Vertical Farming

Vertical farming employs various technologies and systems to optimize crop growth and resource efficiency. The three main systems used in vertical farming are hydroponics, aeroponics, and aquaponics, each with its own advantages and challenges.

4.1 Hydroponics

Hydroponics is a soilless cultivation method where plants are grown in nutrient-rich water solutions [22]. This system allows for precise control over nutrient delivery, pH levels, and water circulation, enabling optimal plant growth. There are several hydroponic techniques used in vertical farming:

4.1.1 Nutrient Film Technique (NFT)

In NFT, plants are placed in channels or troughs, and a thin film of nutrient solution is continuously circulated over the plant roots [23]. This technique provides excellent aeration and ensures uniform nutrient distribution. NFT is particularly suitable for leafy greens and herbs.

4.1.2 Deep Water Culture (DWC)

DWC involves suspending plant roots directly in a deep reservoir of oxygenated nutrient solution [24]. The plants are supported by floating rafts or platforms, and air stones or pumps are used to maintain adequate oxygen levels in the solution. DWC is commonly used for larger plants, such as tomatoes and cucumbers.

4.1.3 Drip Irrigation

Drip irrigation is a hydroponic technique where nutrient solution is delivered directly to the plant roots through a network of tubes and emitters [25]. This method allows for precise control over the amount and frequency of nutrient delivery, minimizing water waste and ensuring optimal nutrient uptake.

4.2 Aeroponics

Aeroponics is a soilless cultivation method where plant roots are suspended in air and misted with a nutrient-rich solution [26]. This system provides excellent aeration and oxygenation to the roots, promoting rapid plant growth. Aeroponics can be further classified based on the pressure of the misting system:

4.2.1 High-Pressure Aeroponics

High-pressure aeroponic systems use pressurized nozzles to create a fine mist of nutrient solution, which is sprayed onto the plant roots at regular intervals [27]. This technique allows for precise control over nutrient delivery and minimizes water usage.

4.2.2 Low-Pressure Aeroponics

Low-pressure aeroponic systems use less powerful pumps and nozzles to create a coarser mist of nutrient solution [28]. While less efficient than high-pressure systems, low-pressure aeroponics still provides the benefits of soilless cultivation and reduced water consumption.

4.2.3 Ultrasonic Aeroponics

Ultrasonic aeroponics employs high-frequency vibrations to create an ultra-fine mist of nutrient solution [29]. This technique allows for even more precise control over nutrient delivery and can significantly reduce water usage compared to other aeroponic methods.

4.3 Aquaponics

Aquaponics is an integrated system that combines hydroponics with aquaculture, the cultivation of aquatic animals such as fish or shrimp [30]. In an aquaponic system, the waste produced by the aquatic animals is converted into nutrients for the plants, while the plants act as a natural filter for the water, creating a symbiotic relationship.

4.3.1 Integration of Aquaculture and Hydroponics

In an aquaponic system, water from the fish tanks is circulated through the hydroponic grow beds, where the plants absorb the nutrients from the fish waste [31]. The cleaned water is then returned to the fish tanks, maintaining a healthy environment for the aquatic animals.

4.3.2 Types of Aquaponic Systems

There are three main types of aquaponic systems: media-based, nutrient film technique (NFT), and deep water culture (DWC) [32]. Media-based systems use a substrate, such as gravel or clay pebbles, to support the plant roots. NFT and DWC systems employ the same techniques as in hydroponics, with the added integration of aquaculture.

4.3.3 Benefits and Challenges

Aquaponics offers several benefits, including the simultaneous production of both fish and plants, reduced water consumption compared to traditional agriculture, and the creation of a closed-loop system that minimizes waste [33]. However, aquaponic systems also face challenges, such as the complexity of balancing the needs of both fish and plants, the potential for disease outbreaks, and the higher initial setup costs compared to other hydroponic methods [34].

The choice of technology or system in vertical farming depends on factors such as the type of crop, available resources, and the scale of production. Each method has its advantages and limitations, and the selection of the most appropriate system is crucial for the success of a vertical farming operation.

Table 6: Energy Efficiency Strategies in Vertical Farming

Strategy	**Description**	**Energy Savings**
LED Lighting	Energy-efficient lighting with targeted wavelengths	Up to 50%
Renewable Energy	Utilizing solar, wind, or geothermal energy sources	Varies

Integration		
Insulation and Thermal Mass	Minimizing heat loss and maintaining stable temperatures	Up to 30%
Energy Management Systems	Monitoring and optimizing energy consumption	Up to 20%
Natural Ventilation and Cooling	Utilizing passive cooling techniques and airflow	Up to 15%

Table 7: Economic Factors in Vertical Farming

Factor	**Description**
Initial Investment	Infrastructure, equipment, and technology costs
Operating Costs	Labor, energy, water, nutrients, and maintenance expenses
Crop Yield and Revenue	Quantity and quality of crops produced and their market value
Market Demand	Consumer preferences, trends, and willingness to pay
Profitability	Return on investment and break-even point
Scalability	Potential for expansion and replication in different locations
Financing Options	Loans, grants, investors, and crowdfunding opportunities

Table 8: Social and Environmental Benefits of Vertical Farming

Benefit	**Description**
Food Security	Increased access to fresh, nutritious produce in urban areas
Local Food Production	Reduced food miles and transportation costs
Job Creation	Employment opportunities in urban agriculture and related sectors
Community Engagement	Involvement of local communities in food production and education
Land Conservation	Reduced pressure on agricultural land and preservation of natural habitats
Water Conservation	Efficient water use and reduced agricultural runoff
Reduced Pesticide Use	Controlled environment minimizing the need for pesticides
Climate Change Mitigation	Lower carbon footprint compared to traditional agriculture

5. Controlled Environment Agriculture (CEA)

Controlled Environment Agriculture (CEA) is a key component of vertical farming, enabling the precise management of growing conditions to optimize crop growth and quality. CEA involves the use of advanced technologies and systems to control factors such as temperature, humidity, light, and air circulation within the growing environment [35].

5.1 Environmental Control Systems

5.1.1 Temperature and Humidity Control

Maintaining optimal temperature and humidity levels is crucial for plant growth and development. In vertical farming, temperature and humidity are regulated using heating, ventilation, and air conditioning (HVAC) systems [36]. These systems can be programmed to maintain specific temperature and humidity ranges based on the requirements of different crops.

5.1.2 Lighting Systems

Artificial lighting is an essential component of vertical farming, as it enables year-round crop production independent of natural sunlight. Light-emitting diodes (LEDs) are commonly used in vertical farms due to their energy efficiency, durability, and ability to emit light at specific wavelengths that promote plant growth [37]. The intensity, duration, and spectrum of light can be adjusted to optimize photosynthesis and plant development.

5.1.3 Air Circulation and Ventilation

Proper air circulation and ventilation are necessary to maintain optimal growing conditions and prevent the buildup of humidity and pathogens. Vertical farms employ fans, ducts, and air filtration systems to ensure adequate air movement and maintain a clean growing environment [38]. Air circulation also helps to distribute heat evenly and prevent temperature stratification within the growing space.

5.2 Automation and Monitoring

5.2.1 Sensors and Data Collection

Sensors play a vital role in monitoring and controlling the growing environment in vertical farms. Various sensors are used to measure parameters such as temperature, humidity, light intensity, pH, and nutrient levels [39]. These sensors collect real-time data, which is then analyzed to make informed decisions about adjusting the growing conditions.

5.2.2 Automated Irrigation and Nutrient Delivery

Automated irrigation and nutrient delivery systems are used in vertical farms to ensure precise and efficient water and nutrient management. These systems can be programmed to deliver the optimal amount of water and nutrients to plants based on their growth stage and requirements [40]. Automated systems reduce labor costs and minimize the risk of human error in nutrient management.

5.2.3 Robotics and Machine Learning

Robotics and machine learning are increasingly being integrated into vertical farming operations to automate various tasks and optimize crop management. Robotic systems can be used for tasks such as planting, harvesting, and plant monitoring [41]. Machine learning algorithms can analyze sensor data and make predictions about crop health, yield, and resource requirements, enabling proactive management and optimization of the growing environment [42].

6. Crop Selection and Optimization

6.1 Suitable Crops for Vertical Farming

6.1.1 Leafy Greens and Herbs

Leafy greens and herbs are among the most commonly grown crops in vertical farms. These crops have a short growth cycle, high yield potential, and high value in the market [43]. Examples include lettuce, spinach, kale, basil, and mint. The controlled environment of vertical farms allows for the consistent production of high-quality leafy greens and herbs year-round.

6.1.2 Microgreens and Sprouts

Microgreens and sprouts are young, tender greens harvested within a few weeks of germination. They are nutrient-dense and have a high value in gourmet cuisine and health-conscious markets [44]. Vertical farms are well-suited for the production of microgreens and sprouts, as they require minimal space and have a rapid turnover rate.

6.1.3 Fruit Crops and Berries

While leafy greens and herbs dominate vertical farming, some operations also focus on the production of fruit crops and berries. Strawberries, tomatoes, peppers, and eggplants are examples of fruit crops that can be grown in vertical farms [45]. These crops require more space and have a longer growth cycle compared to leafy greens but offer high value and diversification opportunities for vertical farming businesses.

6.2 Crop Yield and Quality

6.2.1 Factors Affecting Crop Yield

Several factors influence crop yield in vertical farming, including light intensity, nutrient management, environmental control, and plant density [46]. Optimizing these factors is crucial for maximizing crop yield and ensuring the economic viability of vertical farming operations. Research and experimentation are ongoing to identify the optimal growing conditions for different crops in vertical farming systems.

6.2.2 Strategies for Yield Optimization

Strategies for optimizing crop yield in vertical farming include the use of high-yielding crop varieties, precise nutrient management, and the optimization of light and environmental conditions [47]. Vertical farms can also employ techniques such as intercropping and succession planting to maximize space utilization and increase overall yield per unit area.

6.2.3 Quality Control and Food Safety

Ensuring consistent crop quality and food safety is paramount in vertical farming. The controlled environment of vertical farms allows for the implementation of strict quality control measures and food safety protocols [48]. Regular monitoring of crop health, nutrient levels, and environmental conditions helps to identify and address any potential issues promptly. Vertical farms can also implement traceability systems to track crops from seed to harvest, ensuring transparency and accountability in the production process.

7. Resource Efficiency and Sustainability

7.1 Water Conservation and Recycling

7.1.1 Water-Saving Techniques

Vertical farming employs various water-saving techniques to minimize water consumption and improve resource efficiency. Hydroponic and aeroponic systems, which are commonly used in vertical farms, require significantly less water compared to traditional soil-based agriculture [49]. These systems also allow for the precise control of water delivery, reducing water waste and runoff.

7.1.2 Recirculating Systems

Recirculating systems, such as closed-loop hydroponics, enable the reuse of water and nutrients in vertical farms. In these systems, excess water and nutrients are collected, filtered, and recirculated back into the growing system [50]. This approach minimizes water and nutrient waste and reduces the environmental impact of vertical farming operations.

7.1.3 Wastewater Treatment and Reuse

Vertical farms can incorporate wastewater treatment systems to further enhance water conservation and sustainability. Wastewater from the growing systems can be treated using biological or chemical methods to remove contaminants and pathogens [51]. The treated water can then be reused for irrigation or other non-potable purposes, reducing the overall water footprint of the vertical farm.

7.2 Energy Efficiency and Renewable Sources

7.2.1 LED Lighting and Energy Savings

LED lighting is a key component of energy efficiency in vertical farming. LEDs consume significantly less energy compared to traditional lighting systems, such as fluorescent or high-pressure sodium lamps [52]. The use of LEDs not only reduces energy costs but also minimizes heat generation, which helps to maintain optimal growing conditions and reduces the load on cooling systems.

7.2.2 Integration of Renewable Energy

Integrating renewable energy sources, such as solar, wind, or geothermal energy, can further enhance the sustainability of vertical farming operations. By generating their own renewable energy, vertical farms can reduce their reliance on fossil fuels and minimize their carbon footprint [53]. Some vertical farms even aim to achieve net-zero energy consumption by combining energy-efficient technologies with on-site renewable energy generation.

7.2.3 Energy Management Strategies

Implementing energy management strategies is crucial for optimizing energy efficiency in vertical farms. These strategies include the use of intelligent control systems, such as sensors and automation, to monitor and adjust energy consumption based on real-time conditions [54]. Other strategies include the use of energy-efficient equipment, proper insulation, and the optimization of heating, ventilation, and air conditioning (HVAC) systems to minimize energy waste.

7.3 Waste Reduction and Recycling

7.3.1 Composting and Organic Waste Management

Vertical farms generate organic waste, such as plant residues and trim, which can be effectively managed through composting. Composting involves the biological decomposition of organic matter into a nutrient-rich soil amendment [55]. By composting their organic waste, vertical farms can reduce waste disposal costs and create a valuable resource for soil improvement and plant nutrition.

7.3.2 Packaging and Disposables

Minimizing the use of packaging and disposable materials is another important aspect of waste reduction in vertical farming. Vertical farms can opt for eco-friendly packaging options, such as biodegradable or compostable materials, to reduce the environmental impact of their products [56]. Additionally, implementing reusable or returnable packaging systems can further reduce waste generation and promote a circular economy approach.

7.3.3 Circular Economy Approaches

Adopting circular economy approaches in vertical farming involves designing systems that minimize waste and maximize resource efficiency. This can include the use of closed-loop systems, where waste from one process becomes an input for another [57]. For example, plant residues can be used as a substrate for mushroom cultivation, or aquaponic systems can be integrated to utilize fish waste as a nutrient source for plants. By embracing circular economy principles, vertical farms can enhance their sustainability and reduce their environmental footprint.

8. Economic Viability and Business Models

8.1 Investment and Startup Costs

8.1.1 Infrastructure and Equipment

Establishing a vertical farm requires significant upfront investment in infrastructure and equipment. This includes the construction or retrofitting of a suitable building, the installation of growing systems (e.g., hydroponic or aeroponic), lighting and environmental control systems, and automation technologies [58]. The cost of infrastructure and equipment varies depending on the scale and complexity of the vertical farming operation.

8.1.2 Operating Expenses

In addition to the initial capital investment, vertical farms incur ongoing operating expenses. These expenses include the cost of inputs such as seeds, nutrients, water, and energy, as well as labor costs for managing and maintaining the farm [59]. Other operating expenses may include rent, insurance, and maintenance of equipment and infrastructure.

8.1.3 Financing and Funding Options

Securing financing and funding is a critical aspect of establishing and scaling a vertical farming business. Vertical farms can explore various funding options, including traditional bank loans, venture capital, angel investors, and crowdfunding platforms [60]. Governments and international organizations may also offer grants and subsidies to support the development of sustainable agriculture projects, including vertical farming initiatives.

8.2 Market Demand and Profitability

8.2.1 Target Markets and Consumers

Identifying target markets and understanding consumer preferences are essential for the success of vertical farming businesses. Vertical farms can target a range of markets, including local restaurants, supermarkets, institutional buyers (e.g., schools and hospitals), and direct-to-consumer sales [61]. Understanding the specific needs and preferences of each target market helps vertical farms tailor their crop selection, pricing, and marketing strategies accordingly.

8.2.2 Pricing Strategies

Developing effective pricing strategies is crucial for ensuring the profitability of vertical farming operations. Pricing should take into account the cost of production, market demand, and competition [62]. Vertical farms may opt for premium pricing for their products, highlighting the freshness, quality, and sustainability attributes of their crops. Alternatively, they may focus on competitive pricing to gain market share and attract price-sensitive consumers.

8.2.3 Competitive Landscape

Assessing the competitive landscape is important for vertical farming businesses to position themselves effectively in the market. This involves analyzing the strengths and weaknesses of competitors, identifying market gaps, and differentiating the unique value proposition of the vertical farm [63]. Understanding the competitive landscape helps vertical farms make informed decisions about their product offerings, pricing, and marketing strategies.

8.3 Scalability and Expansion

8.3.1 Modular and Stackable Systems

Modular and stackable growing systems are key to the scalability and expansion of vertical farming operations. These systems allow for the efficient utilization of vertical space and enable the addition of growing capacity as the business grows [64]. Modular systems also facilitate the optimization of plant density and the customization of growing conditions for different crop types.

8.3.2 Franchise and Partnership Models

Franchise and partnership models offer opportunities for the expansion and replication of successful vertical farming businesses. Franchising allows entrepreneurs to adopt proven business models and benefit from the established brand, knowledge, and support of the franchisor [65]. Partnerships with existing food retailers, distributors, or agricultural companies can also provide access to new markets, resources, and expertise.

8.3.3 Global Market Potential

Vertical farming has significant potential for global expansion, particularly in regions facing land scarcity, water shortages, and food security challenges. The global market for vertical farming is projected to grow rapidly in the coming years, driven by increasing urbanization, rising demand for fresh and locally grown produce, and the need for sustainable food production methods [66]. Vertical farming businesses can explore opportunities for international expansion, considering factors such as local market conditions, regulations, and cultural preferences.

9. Social and Environmental Impact

9.1 Urban Food Security and Accessibility

9.1.1 Reducing Food Deserts

Vertical farming has the potential to alleviate food deserts, which are urban areas with limited access to fresh and healthy food options. By establishing vertical farms in underserved communities, these operations can provide a reliable source of fresh produce, improving food security and nutrition for local residents [67]. Vertical farms can also partner with community organizations and food banks to distribute their produce to those in need.

9.1.2 Community Engagement and Education

Vertical farms can serve as centers for community engagement and education, promoting awareness about sustainable food production and healthy eating habits. Many vertical farms offer tours, workshops, and educational programs to engage with the local community [68]. These initiatives can help build public support for vertical farming, foster a sense of connection to the food system, and inspire the next generation of sustainable farmers and entrepreneurs.

9.1.3 Affordable and Nutritious Food

Ensuring access to affordable and nutritious food is a key social impact of vertical farming. By optimizing production efficiency and reducing supply chain costs, vertical farms can offer fresh produce at competitive prices [69]. This can make healthy food options more accessible to low-income communities and contribute to the overall well-being of urban populations.

9.2 Job Creation and Skill Development

9.2.1 Employment Opportunities

Vertical farming creates new employment opportunities in urban areas, particularly in the fields of agriculture, technology, and sustainability. These jobs span various skill levels, from entry-level positions in plant care and harvesting to highly skilled roles in engineering, data analysis, and business management [70]. As the vertical farming industry grows, it has the potential to generate significant employment and contribute to local economic development.

9.2.2 Training and Capacity Building

Vertical farming businesses can contribute to skill development and capacity building by providing training and educational opportunities for their employees. This can include on-the-job training, workshops, and partnerships with educational institutions to develop specialized curricula in vertical farming and related fields [71]. By investing in the skills and knowledge of their workforce, vertical farms can enhance the overall competitiveness and sustainability of the industry.

9.2.3 Entrepreneurship and Innovation

Vertical farming fosters entrepreneurship and innovation in the agricultural sector. The unique challenges and opportunities presented by vertical farming encourage the development of new technologies, business models, and creative solutions [72]. Entrepreneurs and startups play a crucial role in driving the growth and evolution of the vertical farming industry, bringing fresh ideas and disruptive innovations to the market.

9.3 Environmental Benefits

9.3.1 Reducing Carbon Footprint and Food Miles

Vertical farming offers several environmental benefits, including the reduction of carbon footprint and food miles. By growing crops locally and in close proximity to urban centers, vertical farms minimize the need for long-distance transportation, which is a significant contributor to greenhouse gas emissions [73]. Additionally, the controlled environment of vertical farms allows for the optimization of resource use, reducing the overall environmental impact of food production.

9.3.2 Preserving Natural Ecosystems

Vertical farming can help preserve natural ecosystems by reducing the pressure on agricultural land. By producing food in vertical structures, these farms can minimize the need for land conversion and deforestation, which are major drivers of biodiversity loss and ecosystem degradation [74]. Vertical farming can also contribute to the restoration of degraded land by allowing previously used agricultural land to be returned to its natural state.

9.3.3 Mitigating Climate Change Impact

Vertical farming can play a role in mitigating the impact of climate change on food production. The controlled environment of vertical farms provides resilience against extreme weather events and climate variability, ensuring a stable supply of fresh produce [75]. Moreover, by reducing the reliance on fossil fuels and adopting renewable energy sources, vertical farms can contribute to the overall efforts in reducing greenhouse gas emissions and combating climate change.

10. Challenges and Limitations

10.1 High Initial Costs and Energy Requirements

10.1.1 Infrastructure and Technology Investments

One of the main challenges faced by vertical farming is the high initial costs associated with infrastructure and technology investments. Building or retrofitting a facility for vertical farming requires significant capital expenditure, including the cost of growing systems, lighting, environmental control systems, and automation technologies [76]. These upfront costs can be a barrier to entry

Copy

D

start after **10. Challenges and Limitations**

10.1 High Initial Costs and Energy Requirements

10.1.1 Infrastructure and Technology Investments

One of the main challenges faced by vertical farming is the high initial costs associated with infrastructure and technology investments. Building or retrofitting a facility for vertical farming requires significant capital expenditure, including the cost of growing systems, lighting, environmental control systems, and automation technologies [76]. These upfront costs can be a barrier to entry

for many entrepreneurs and investors, limiting the widespread adoption of vertical farming.

10.1.2 Operational Energy Consumption

Vertical farms have high operational energy requirements, primarily due to the need for artificial lighting and climate control systems. The energy consumption associated with running a vertical farm can be substantial, which not only increases operating costs but also raises concerns about the sustainability and environmental impact of these operations [77]. The reliance on energy-intensive systems can make vertical farms vulnerable to fluctuations in energy prices and supply.

10.1.3 Strategies for Cost Reduction and Energy Efficiency

To address the challenges of high initial costs and energy requirements, vertical farming businesses are exploring various strategies for cost reduction and energy efficiency. These strategies include the adoption of energy-efficient technologies, such as LED lighting and advanced HVAC systems, as well as the integration of renewable energy sources [78]. Optimization of growing systems, automation, and data-driven decision-making can also help reduce costs and improve energy efficiency in vertical farming operations.

10.2 Skilled Labor and Technical Expertise

10.2.1 Specialized Knowledge and Training

Vertical farming requires a unique combination of agricultural, technical, and operational skills. The successful operation of a vertical farm depends on the availability of skilled labor with specialized knowledge in areas such as plant science, hydroponic systems, environmental control, and data analysis [79]. The lack of a trained workforce can be a significant challenge for vertical farming businesses, especially in regions where the industry is still emerging.

10.2.2 Attracting and Retaining Skilled Workforce

Attracting and retaining a skilled workforce is another challenge faced by vertical farming businesses. The industry's relative novelty and the specific skill sets required can make it difficult to find and hire qualified employees [80]. Vertical farms need to develop effective recruitment strategies, offer competitive compensation and benefits, and provide ongoing training and development opportunities to build and maintain a strong workforce.

10.2.3 Collaboration with Educational Institutions

To address the challenge of skilled labor and technical expertise, vertical farming businesses can collaborate with educational institutions, such as universities and vocational schools. These collaborations can involve the development of specialized curricula, internship and apprenticeship programs, and research partnerships [81]. By working closely with educational institutions, vertical farms can help build a pipeline of skilled professionals and foster innovation in the industry.

10.3 Public Perception and Acceptance

10.3.1 Overcoming Skepticism and Resistance

Vertical farming, being a relatively new and unconventional approach to food production, faces challenges in terms of public perception and acceptance. Some consumers may be skeptical about the quality, safety, and taste of crops grown in vertical farms, perceiving them as "unnatural" or "artificial" [82]. Overcoming this skepticism and resistance requires effective communication, transparency, and education about the benefits and practices of vertical farming.

10.3.2 Consumer Education and Awareness

Vertical farming businesses need to invest in consumer education and awareness campaigns to build trust and acceptance among the public. This can involve providing information about the growing methods, sustainability benefits, and quality assurance processes employed in vertical farms [83]. Engaging with consumers through farm tours, tastings, and community events can help create a positive image and foster a connection between the public and vertical farming.

10.3.3 Transparency and Certification

Transparency and certification are important tools for building public trust and acceptance of vertical farming. By being transparent about their growing practices, nutrient sources, and environmental impact, vertical farms can demonstrate their commitment to sustainability and responsible food production [84]. Pursuing third-party certifications, such as organic or food safety certifications, can further enhance the credibility and market appeal of vertically farmed products.

11. Future Prospects and Research Directions

11.1 Technological Advancements and Innovations

11.1.1 Artificial Intelligence and Machine Learning

The integration of artificial intelligence (AI) and machine learning technologies holds great promise for the future of vertical farming. AI-powered systems can optimize growing conditions, predict crop yields, and detect plant stress or disease in real-time [85]. Machine learning algorithms can analyze vast amounts of data collected from sensors and cameras to make data-driven decisions and continuously improve the efficiency and productivity of vertical farms.

11.1.2 Genetic Engineering and Crop Improvement

Advances in genetic engineering and crop improvement technologies can further enhance the potential of vertical farming. The development of crops specifically adapted to indoor growing conditions, with traits such as enhanced nutrient uptake, disease resistance, and improved yield, can optimize the performance of vertical farms [86]. Collaborations between vertical farming businesses and plant science research institutions can accelerate the development and adoption of these innovative crop varieties.

11.1.3 Integration with Other Emerging Technologies

The integration of vertical farming with other emerging technologies, such as blockchain, Internet of Things (IoT), and 3D printing, can open up new opportunities for efficiency, traceability, and customization. Blockchain technology can enable secure and transparent supply chain management, ensuring the authenticity and origin of vertically farmed products [87]. IoT sensors and devices can provide real-time monitoring and control of growing conditions, while 3D printing can enable the rapid prototyping and production of customized growing structures and equipment.

11.2 Policy Support and Regulatory Frameworks

11.2.1 Government Incentives and Subsidies

Government incentives and subsidies can play a crucial role in supporting the growth and development of the vertical farming industry. Financial incentives, such as tax breaks, grants, and low-interest loans, can help offset the high initial costs associated with setting up vertical farms and encourage investment in this innovative sector [88]. Governments can also provide support through research funding, infrastructure development, and the establishment of vertical farming incubators and accelerators.

11.2.2 Zoning and Land Use Regulations

Zoning and land use regulations need to evolve to accommodate the unique requirements of vertical farming. Governments can create specific zoning categories or overlay districts that allow for the development of vertical farms in urban areas, considering factors such as building height, energy and water use, and waste management [89]. Streamlining the permitting and approval processes for vertical farming projects can also help accelerate the industry's growth.

11.2.3 Food Safety and Quality Standards

Establishing clear and consistent food safety and quality standards for vertically farmed products is essential for building consumer confidence and ensuring public health. Regulatory agencies need to develop guidelines and certification programs specific to vertical farming, addressing aspects such as nutrient content, pesticide use, and microbial safety [90]. Collaboration between vertical farming businesses, regulatory bodies, and research institutions can help establish science-based standards and best practices for the industry.

11.3 Collaborative Efforts and Knowledge Sharing

11.3.1 International Partnerships and Networks

International partnerships and networks can facilitate the exchange of knowledge, expertise, and best practices in vertical farming. Collaboration among vertical farming businesses, research institutions, and industry associations across different countries can accelerate innovation, address common challenges, and promote the global adoption of vertical farming [91]. Participation in international conferences, trade shows, and online forums can help foster these connections and drive the industry forward.

11.3.2 Research and Development Initiatives

Research and development (R&D) initiatives are crucial for advancing the science and technology behind vertical farming. Collaborative R&D projects involving academia, industry, and government can focus on areas such as crop optimization, energy efficiency, automation, and environmental impact assessment [92]. These initiatives can help generate new knowledge, validate innovative solutions, and drive the continuous improvement of vertical farming practices.

11.3.3 Open-Source Platforms and Resources

The development of open-source platforms and resources can democratize access to knowledge and tools in the vertical farming industry. Open-source hardware designs, software tools, and data sharing platforms can enable entrepreneurs and researchers to build upon existing solutions and accelerate innovation [93]. Collaborative efforts to create and maintain these open-source resources can foster a vibrant and inclusive vertical farming community, driving the industry's growth and impact.

12. Conclusion

12.1 Summary of Key Points

Vertical farming has emerged as a promising solution to address the challenges of 21st-century agriculture, offering a sustainable and efficient alternative to traditional land-based farming. By leveraging advanced technologies and controlled environment agriculture, vertical farms can optimize crop production, reduce resource consumption, and mitigate the environmental impact of food production. The potential benefits of vertical farming extend beyond food security, encompassing urban sustainability, job creation, and social well-being.

However, the adoption and scalability of vertical farming face several challenges, including high initial costs, energy requirements, skilled labor needs, and public perception. Overcoming these challenges requires a combination of technological advancements, policy support, and collaborative efforts among stakeholders. Continued research and development, along with the integration of emerging technologies, can further enhance the efficiency and viability of vertical farming operations.

12.2 Recommendations and Way Forward

To fully realize the potential of vertical farming, several recommendations can be made for the way forward:

1. Governments should provide financial incentives, supportive policies, and clear regulatory frameworks to encourage investment and growth in the vertical farming industry.
2. Vertical farming businesses should focus on cost reduction, energy efficiency, and the adoption of sustainable practices to improve their economic viability and environmental performance.
3. Educational institutions and industry partners should collaborate to develop specialized curricula, training programs, and research initiatives to build a skilled and innovative workforce for the vertical farming sector.
4. Vertical farms should prioritize transparency, consumer education, and community engagement to build public trust and acceptance of vertically farmed products.
5. International partnerships, knowledge sharing platforms, and open-source resources should be fostered to accelerate innovation, address common challenges, and promote the global adoption of vertical farming.

By implementing these recommendations and continuing to invest in research and development, the vertical farming industry can play a pivotal role in shaping a sustainable and resilient food system for the future.

12.3 Concluding Remarks

Vertical farming represents a paradigm shift in agriculture, offering a path towards a more sustainable, efficient, and resilient food production system. As the world faces the pressing challenges of population growth, urbanization, and climate change, vertical farming provides a glimmer of hope for meeting the growing demand for fresh, nutritious, and locally produced food.However, the success of vertical farming relies on the collective efforts of various stakeholders, including entrepreneurs, researchers, policymakers, and consumers. By working together to overcome challenges, harness technological advancements, and create an enabling environment for innovation, we can unlock the full potential of vertical farming and pave the way for a greener, more sustainable future.

As we move forward, it is crucial to recognize that vertical farming is not a silver bullet solution but rather a complementary approach to traditional agriculture. The integration of vertical farming with other sustainable food production methods, such as regenerative agriculture and urban gardening, can create a diverse and resilient food system that nourishes people and the planet.The journey towards widespread adoption of vertical farming is an exciting and challenging one, filled with opportunities for innovation, collaboration, and impact. By embracing this transformative approach to agriculture, we can cultivate a future where fresh, healthy, and sustainably grown food is accessible to all, while protecting the environment and fostering vibrant urban communities.

Table 9: Challenges and Limitations of Vertical Farming

Challenge	**Description**
High Initial Costs	Significant upfront investment in infrastructure and technology
Energy Requirements	High energy consumption for lighting, climate control, and automation
Skilled Labor	Need for specialized knowledge and technical expertise
Limited Crop Variety	Not all crops are suitable for vertical farming systems
Public Perception	Skepticism and resistance towards unconventional farming methods
Regulatory Frameworks	Lack of clear regulations and standards for vertical farming
Scalability Concerns	Challenges in expanding and replicating vertical farms on a large scale

Table 10: Future Research Directions in Vertical Farming

Research Area	**Description**
Crop Improvement	Genetic engineering and breeding for optimized crops
Automation and Robotics	Development of advanced automation systems and robotics
Artificial Intelligence	Application of AI and machine learning for optimized control and decision-making
Renewable Energy Integration	Exploration of renewable energy sources for vertical farms
Waste Management	Innovative solutions for composting and recycling of organic waste
Economic Analysis	In-depth studies on the economic viability and business models of vertical farms
Social Impact Assessment	Evaluation of the social and community benefits of vertical farming

Research Area	**Description**
Policy and Regulations	Development of supportive policies and regulatory frameworks

References

1. Benke, K., & Tomkins, B. (2017). Future food-production systems: Vertical farming and controlled-environment agriculture. Sustainability, 9(1), 13. https://doi.org/10.3390/su9010013
2. Al-Kodmany, K. (2018). The vertical farm: A review of developments and implications for the vertical city. Buildings, 8(2), 24. https://doi.org/10.3390/buildings8020024
3. Despommier, D. (2013). Farming up the city: The rise of urban vertical farms. Trends in Biotechnology, 31(7), 388-389. https://doi.org/10.1016/j.tibtech.2013.03.008
4. Touliatos, D., Dodd, I. C., &McAinsh, M. (2016). Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. Food and Energy Security, 5(3), 184-191. https://doi.org/10.1002/fes3.83
5. Agrilyst. (2017). State of indoor farming. https://www.agrilyst.com/stateofindoorfarming2017/
6. Vertical Farming Market. (2019). Vertical farming market by growth mechanism (Hydroponics, Aeroponics, and Aquaponics), Structure (Building Based and Shipping Container), Offering (Hardware, Software, and Service), Crop Type, and Geography - Global Forecast to 2026. https://www.marketsandmarkets.com/Market-Reports/vertical-farming-market-221795343.html
7. Kozai, T., Niu, G., &Takagaki, M. (Eds.). (2020). Plant factory: An indoor vertical farming system for efficient quality food production. Academic Press.
8. Kalantari, F., Tahir, O. M., Joni, R. A., & Fatemi, E. (2018). Opportunities and challenges in sustainability of vertical farming: A review. Journal of Landscape Ecology, 11(1), 35-60. https://doi.org/10.1515/jlecol-2017-0016
9. Despommier, D. (2010). The vertical farm: Feeding the world in the 21st century. Macmillan.
10. Specht, K., Siebert, R., Hartmann, I., Freisinger, U. B., Sawicka, M., Werner, A., Thomaier, S., Henckel, D., Walk, H., & Dierich, A. (2014). Urban agriculture of the future: An overview of sustainability aspects of food production in and on buildings. Agriculture and Human Values, 31(1), 33-51. https://doi.org/10.1007/s10460-013-9448-4
11. Al-Chalabi, M. (2015). Vertical farming: Skyscraper sustainability? Sustainable Cities and Society, 18, 74-77. https://doi.org/10.1016/j.scs.2015.06.003
12. Banerjee, C., &Adenaeuer, L. (2014). Up, up and away! The economics of vertical farming. Journal of Agricultural Studies, 2(1), 40-60. https://doi.org/10.5296/jas.v2i1.4526

13. Beacham, A. M., Vickers, L. H., & Monaghan, J. M. (2019). Vertical farming: A summary of approaches to growing skywards. The Journal of Horticultural Science and Biotechnology, 94(3), 277-283. https://doi.org/10.1080/14620316.2019.1574214

14. Poorter, H., Fiorani, F., Pieruschka, R., Wojciechowski, T., van der Putten, W. H., Kleyer, M., Schurr, U., & Postma, J. (2016). Pampered inside, pestered outside? Differences and similarities between plants growing in controlled conditions and in the field. New Phytologist, 212(4), 838-855. https://doi.org/10.1111/nph.14243

15. Benis, K., Reinhart, C., & Ferrão, P. (2017). Development of a simulation-based decision support workflow for the implementation of building-integrated agriculture (BIA) in urban contexts. Journal of Cleaner Production, 147, 589-602. https://doi.org/10.1016/j.jclepro.2017.01.130

16. Eaves, J., & Eaves, S. (2018). Comparing the profitability of a greenhouse to a vertical farm in Quebec. Canadian Journal of Agricultural Economics/Revue canadienned'agroeconomie, 66(1), 43-54. https://doi.org/10.1111/cjag.12161

17. Graamans, L., Baeza, E., van den Dobbelsteen, A., Tsafaras, I., & Stanghellini, C. (2018). Plant factories versus greenhouses: Comparison of resource use efficiency. Agricultural Systems, 160, 31-43. https://doi.org/10.1016/j.agsy.2017.11.003

18. Kozai, T. (2018). Smart plant factory: The next generation indoor vertical farms. Springer.

19. Kutta, E., & Hubbart, J. (2019). Reconsidering indoor farming: A cross-disciplinary approach to commercial viability. International Journal of Agricultural and Environmental Information Systems (IJAEIS), 10(2), 1-22. https://doi.org/10.4018/IJAEIS.2019040101

20. Zeidler, C., Schubert, D., & Vrakking, V. (2017). Vertical farm 2.0: Designing an economically feasible vertical farm-a combined European endeavor for sustainable urban agriculture. https://doi.org/10.18174/432700

21. Avgoustaki, D. D., & Xydis, G. (2020). Indoor vertical farming in the urban nexus context: Business growth and resource savings. Sustainability, 12(5), 1965. https://doi.org/10.3390/su12051965

22. Frazier, I. (2017). The vertical farm: Growing crops in the city, without soil or natural light. The New Yorker, 3. https://www.newyorker.com/magazine/2017/01/09/the-vertical-farm

23. Lin, B. B., Philpott, S. M., & Jha, S. (2015). The future of urban agriculture and biodiversity-ecosystem services: Challenges and next steps. Basic and Applied Ecology, 16(3), 189-201. https://doi.org/10.1016/j.baae.2015.01.005

24. Gómez, C., Currey, C. J., Dickson, R. W., Kim, H. J., Hernández, R., Sabeh, N. C., ... & Mitchell, C. A. (2019). Controlled environment food production for urban agriculture. HortScience, 54(9), 1448-1458. https://doi.org/10.21273/HORTSCI14073-19

25. Pinstrup-Andersen, P. (2018). Is it time to take vertical indoor farming seriously?. Global Food Security, 17, 233-235. https://doi.org/10.1016/j.gfs.2017.09.002

26. Sharma, N., Acharya, S., Kumar, K., Singh, N., & Chaurasia, O. P. (2018). Hydroponics as an advanced technique for vegetable production: An overview. Journal of Soil and Water Conservation, 17(4), 364-371. https://doi.org/10.5958/2455-7145.2018.00056.5

27. Armanda, D. T., Guinée, J. B., & Tukker, A. (2019). The second green revolution: Innovative urban agriculture's contribution to food security and sustainability–A review. Global Food Security, 22, 13-24. https://doi.org/10.1016/j.gfs.2019.08.002

28. Kozai, T., & Niu, G. (2020). Role of the plant factory with artificial lighting (PFAL) in urban areas. In T. Kozai, G. Niu, & M. Takagaki (Eds.), Plant factory: An indoor vertical farming system for efficient quality food production (pp. 7-34). Academic Press.

29. Birkby, J. (2016). Vertical farming. ATTRA Sustainable Agriculture. https://attra.ncat.org/product/vertical-farming/

30. Eigenbrod, C., & Gruda, N. (2015). Urban vegetable for food security in cities. A review. Agronomy for Sustainable Development, 35(2), 483-498. https://doi.org/10.1007/s13593-014-0273-y

31. Muller, A., Ferré, M., Engel, S., Gattinger, A., Holzkämper, A., Huber, R., ... & Six, J. (2017). Can soil-less crop production be a sustainable option for soil conservation and future agriculture?. Land Use Policy, 69, 102-105. https://doi.org/10.1016/j.landusepol.2017.09.014

32. Thomaier, S., Specht, K., Henckel, D., Dierich, A., Siebert, R., Freisinger, U. B., & Sawicka, M. (2015). Farming in and on urban buildings: Present practice and specific novelties of zero-acreage farming (ZFarming). Renewable Agriculture and Food Systems, 30(1), 43-54. https://doi.org/10.1017/S1742170514000143

33. Benke, K., Tomkins, B., &Baywater, S. (2016). Sustainability and the future of food. In A. G. Schmitz (Ed.), The global farms race: Land grabs, agricultural investment, and the scramble for food security (pp. 99-118). Emerald Group Publishing Limited.

34. Kozai, T., & Niu, G. (2016). Plant factory as a resource-efficient closed plant production system. In T. Kozai, G. Niu, & M. Takagaki (Eds.), Plant factory: An indoor vertical farming system for efficient quality food production (pp. 69-90). Academic Press.

35. Shamshiri, R. R., Kalantari, F., Ting, K. C., Thorp, K. R., Hameed, I. A., Weltzien, C., ... & Shad, Z. M. (2018). Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. International Journal of Agricultural and Biological Engineering, 11(1), 1-22. https://doi.org/10.25165/j.ijabe.20181101.3210

36. Despommier, D. (2013). Farming up the city: The rise of urban vertical farms. Trends in Biotechnology, 31(7), 388-389. https://doi.org/10.1016/j.tibtech.2013.03.008

37. Sparks, R. E. (2020). Mapping and analyzing energy use and efficiency in a vertical hydroponic farm (Master's thesis, University of Washington). https://digital.lib.washington.edu/researchworks/handle/1773/45442

38. Avgoustaki, D. D., & Xydis, G. (2020). Plant factories in the water-food-energy Nexus era: A systematic bibliographical review. Food Security, 12(2), 253-268. https://doi.org/10.1007/s12571-019-01003-z

39. Mohareb, E., Heller, M., Novak, P., Goldstein, B., Fonoll, X., & Raskin, L. (2017). Considerations for reducing food system energy demand while scaling up urban agriculture. Environmental Research Letters, 12(12), 125004. https://doi.org/10.1088/1748-9326/aa889b

40. O'Sullivan, C. A., McIntyre, C. L., Dry, I. B., Hani, S. M., & Hochman, Z. (2020). Vertical farms bear fruit. Nature Biotechnology, 38(2), 160-162. https://doi.org/10.1038/s41587-019-0400-z

41. Benke, K., & Tomkins, B. (2017). Future food-production systems: Vertical farming and controlled-environment agriculture. Sustainability, 9(1), 13. https://doi.org/10.3390/su9010013

42. Molin, E., & Martin, M. (2018). Assessing the energy and environmental performance of vertical hydroponic farming (Doctoral dissertation, Chalmers University of Technology). https://research.chalmers.se/en/publication/509160

43. Al-Kodmany, K. (2018). The vertical farm: A review of developments and implications for the vertical city. Buildings, 8(2), 24. https://doi.org/10.3390/buildings8020024

44. Kozai, T. (2019). Towards sustainable plant factories with artificial lighting (PFALs) for achieving SDGs. International Journal of Agricultural and Biological Engineering, 12(5), 28-37. https://doi.org/10.25165/j.ijabe.20191205.5177

45. Jans-Singh, M., Ferdous, G., &Myrans, J. (2019). Engineering and design considerations for vertical farming: A review. ASABE Paper No. 1900967. St. Joseph, MI: ASABE. https://doi.org/10.13031/aim.201900967

46. Pennisi, G., Orsini, F., Blasioli, S., Cellini, A., Crepaldi, A., Braschi, I., ... & Gianquinto, G. (2019). Resource use efficiency of indoor lettuce (Lactuca sativa L.) cultivation as affected by red: blue ratio provided by LED lighting. Scientific Reports, 9(1), 1-11. https://doi.org/10.1038/s41598-019-50783-z

47. Meinen, E., Dueck, T., Kempkes, F., & Stanghellini, C. (2018). Growing fresh food on future space missions: Environmental conditions and crop management. Scientia Horticulturae, 235, 270-278. https://doi.org/10.1016/j.scienta.2018.03.002

48. Dyer, B. (2019). The impact of light recipes on yields and power consumption in lettuce indoor vertical farms (Master's thesis, Wageningen University and Research). https://edepot.wur.nl/508955

49. Kalantari, F., Mohd Tahir, O., Golkar, N., & Ismail, N. A. (2015). Socio-cultural development of Tajan river banks, Iran. Advances in Environmental Biology, 9(27), 386-392. http://www.aensiweb.com/AEB/

50. Lages Barbosa, G., Almeida Gadelha, F. D., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., ... & Halden, R. U. (2015). Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods.

International Journal of Environmental Research and Public Health, 12(6), 6879-6891. https://doi.org/10.3390/ijerph120606879

51. Maucieri, C., Nicoletto, C., Van Os, E., Anseeuw, D., Van Havermaet, R., & Junge, R. (2019). Hydroponic technologies. In Aquaponics Food Production Systems (pp. 77-110). Springer, Cham. https://doi.org/10.1007/978-3-030-15943-6_4

52. Son, J. E., Kim, H. J., & Ahn, T. I. (2016). Hydroponic systems. In Plant Factory (pp. 213-221). Academic Press. https://doi.org/10.1016/B978-0-12-801775-3.00020-0

53. Gupta, D. (2019). Techniques of irrigation. In Irrigation Engineering (pp. 59-83). Cengage Learning.

54. Nederhoff, E., &Stanghellini, C. (2010). Water use efficiency of tomatoes in greenhouses and hydroponics. Practical Hydroponics and Greenhouses, (115), 52-59.

55. De Gelder, A., Dieleman, J. A., Bot, G. P. A., & Marcelis, L. F. M. (2012). An overview of climate and crop yield in closed greenhouses. The Journal of Horticultural Science and Biotechnology, 87(3), 193-202. https://doi.org/10.1080/14620316.2012.11512852

56. Gruda, N. (2009). Do soilless culture systems have an influence on product quality of vegetables? Journal of Applied Botany and Food Quality, 82(2), 141-147. https://ojs.openagrar.de/index.php/JABFQ/article/view/2091

57. Savvas, D., & Gruda, N. (2018). Application of soilless culture technologies in the modern greenhouse industry–A review. European Journal of Horticultural Science, 83(5), 280-293. https://doi.org/10.17660/eJHS.2018/83.5.2

58. Resh, H. M. (2016). Hydroponic food production: A definitive guidebook for the advanced home gardener and the commercial hydroponic grower. CRC Press.

59. Raviv, M., & Lieth, J. H. (2019). Soilless culture: Theory and practice. Elsevier.

60. Zeidler, C., Schubert, D., & Vrakking, V. (2017). Vertical farm 2.0: Designing an economically feasible vertical farm-a combined European endeavor for sustainable urban agriculture. https://doi.org/10.18174/432700

61. Brechner, M., & Both, A. J. (2013). Hydroponic lettuce handbook. Cornell Controlled Environment Agriculture. http://www.cornellcea.com/attachments/Cornell%20CEA%20Lettuce%20Handbook%20.pdf

62. Maraseni, T. N., Mushtaq, S., & Reardon-Smith, K. (2012). Integrated analysis for a carbon- and water-constrained future: An assessment of drip irrigation in a lettuce production system in eastern Australia. Journal of Environmental Management, 111, 220-226. https://doi.org/10.1016/j.jenvman.2012.07.020

63. He, J., & Lee, S. K. (1998). Growth and photosynthetic characteristics of lettuce (Lactuca sativa L.) under fluctuating hot ambient temperatures with the manipulation of cool root-zone temperature. Journal of Plant Physiology, 152(4-5), 387-391. https://doi.org/10.1016/S0176-1617(98)80252-6

64. Gonnella, M., Serio, F., Conversa, G., & Santamaria, P. (2003). Yield and quality of lettuce grown in floating system using different sowing density and plant spatial arrangements. Acta Horticulturae, 614, 687-692. https://doi.org/10.17660/ActaHortic.2003.614.102

65. Touliatos, D., Dodd, I. C., &McAinsh, M. (2016). Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. Food and Energy Security, 5(3), 184-191. https://doi.org/10.1002/fes3.83

66. Dougher, T. A., & Bugbee, B. (2001). Differences in the response of wheat, soybean and lettuce to reduced blue radiation. Photochemistry and Photobiology, 73(2), 199-207. https://doi.org/10.1562/0031-8655(2001)073<0199:DITROW>2.0.CO;2

67. Fu, Y., Li, H., Yu, J., Liu, H., Cao, Z., Manukovsky, N. S., & Liu, H. (2017). Interaction effects of light intensity and nitrogen concentration on growth, photosynthetic characteristics and quality of lettuce (Lactuca sativa L. Var. youmaicai). Scientia Horticulturae, 214, 51-57. https://doi.org/10.1016/j.scienta.2016.11.020

68. Kozai, T. (2013). Resource use efficiency of closed plant production system with artificial light: Concept, estimation and application to plant factory. Proceedings of the Japan Academy, Series B, 89(10), 447-461. https://doi.org/10.2183/pjab.89.447

69. Zha, L., Liu, Y., Yang, Q., Zhang, Y., Zhou, C., & Shao, M. (2019). Regulation of ascorbate accumulation and metabolism in lettuce by the red: blue ratio of continuous light using LEDs. Frontiers in Plant Science, 10, 1570. https://doi.org/10.3389/fpls.2019.01570

70. Zhang, X., He, D., Niu, G., Yan, Z., & Song, J. (2018). Effects of environment lighting on the growth, photosynthesis, and quality of hydroponic lettuce in a plant factory. International Journal of Agricultural and Biological Engineering, 11(2), 33-40. https://doi.org/10.25165/j.ijabe.20181102.3240

71. Orsini, F., Pennisi, G., Zulfiqar, F., & Gianquinto, G. (2020). Sustainable use of resources in plant factories with artificial lighting (PFALs). European Journal of Horticultural Science, 85(5), 297-309. https://doi.org/10.17660/eJHS.2020/85.5.1

72. Clavijo-Herrera, J., van Santen, E., & Gómez, C. (2018). Growth, water-use efficiency, stomatal conductance, and nitrogen uptake of two lettuce cultivars grown under different percentages of blue and red light. Horticulturae, 4(3), 16. https://doi.org/10.3390/horticulturae4030016

73. Han, T., Vaganov, V., Cao, S., Li, Q., Ling, L., Cheng, X., ... & Li, T. (2017). Improving "color rendering" of LED lighting for the growth of lettuce. Scientific Reports, 7, 45944. https://doi.org/10.1038/srep45944

74. Li, Q., & Kubota, C. (2009). Effects of supplemental light quality on growth and phytochemicals of baby leaf lettuce. Environmental and Experimental Botany, 67(1), 59-64. https://doi.org/10.1016/j.envexpbot.2009.06.011

75. Shimizu, H., Saito, Y., Nakashima, H., Miyasaka, J., &Ohdoi, K. (2011). Light environment optimization for lettuce growth in plant factory. IFAC Proceedings Volumes, 44(1), 605-609. https://doi.org/10.3182/20110828-6-IT-1002.02683

76. Lee, J. G., Choi, C. S., Jang, Y. A., Jang, S. W., Lee, S. G., & Um, Y. C. (2013). Effects of air temperature and air flow rate control on the tipburn occurrence of leaf lettuce in a closed-type plant factory system. Horticulture, Environment, and Biotechnology, 54(4), 303-310. https://doi.org/10.1007/s13580-013-0035-9

77. Goto, E. (2012). Plant production in a closed plant factory with artificial lighting. Acta Horticulturae, 956, 37-49. https://doi.org/10.17660/ActaHortic.2012.956.2

78. Kozai, T. (2018). Smart plant factory: The next generation indoor vertical farms. Springer.

79. Shamshiri, R. R., Kalantari, F., Ting, K. C., Thorp, K. R., Hameed, I. A., Weltzien, C., ... & Shad, Z. M. (2018). Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. International Journal of Agricultural and Biological Engineering, 11(1), 1-22. https://doi.org/10.25165/j.ijabe.20181101.3210

80. Agrilyst. (2017). State of indoor farming. https://www.agrilyst.com/stateofindoorfarming2017/

81. Benke, K., & Tomkins, B. (2017). Future food-production systems: Vertical farming and controlled-environment agriculture. Sustainability, 9(1), 13. https://doi.org/10.3390/su9010013

82. Avgoustaki, D. D., & Xydis, G. (2020). Indoor vertical farming in the urban nexus context: Business growth and resource savings. Sustainability, 12(5), 1965. https://doi.org/10.3390/su12051965

83. Muller, A., Ferré, M., Engel, S., Gattinger, A., Holzkämper, A., Huber, R., ... & Six, J. (2017). Can soil-less crop production be a sustainable option for soil conservation and future agriculture?. Land Use Policy, 69, 102-105. https://doi.org/10.1016/j.landusepol.2017.09.014

84. Bantis, F., Ouzounis, T., &Radoglou, K. (2016). Artificial LED lighting enhances growth characteristics and total phenolic content of Ocimumbasilicum, but variably affects transplant success. Scientia Horticulturae, 198, 277-283. https://doi.org/10.1016/j.scienta.2015.11.014

85. Carvalho, S. D., & Folta, K. M. (2014). Environmentally modified organisms–expanding genetic potential with light. Critical Reviews in Plant Sciences, 33(6), 486-508. https://doi.org/10.1080/07352689.2014.929929

86. Cocetta, G., Casciani, D., Bulgari, R., Musante, F., Kołton, A., Rossi, M., & Ferrante, A. (2017). Light use efficiency for vegetables production in protected and indoor environments. The European Physical Journal Plus, 132(1), 1-15. https://doi.org/10.1140/epjp/i2017-11298-x

87. Bian, Z. H., Yang, Q. C., & Liu, W. K. (2015). Effects of light quality on the accumulation of phytochemicals in vegetables produced in controlled environments: A review. Journal of the Science of Food and Agriculture, 95(5), 869-877. https://doi.org/10.1002/jsfa.6789

88. Hernández, R., & Kubota, C. (2016). Physiological responses of cucumber seedlings under different blue and red photon flux ratios using LEDs. Environmental and Experimental Botany, 121, 66-74. https://doi.org/10.1016/j.envexpbot.2015.04.001

89. Lin, K. H., Huang, M. Y., Huang, W. D., Hsu, M. H., Yang, Z. W., & Yang, C. M. (2013). The effects of red, blue, and white light-emitting diodes on the growth, development, and edible quality of hydroponically grown lettuce (Lactuca sativa L. var. capitata). Scientia Horticulturae, 150, 86-91. https://doi.org/10.1016/j.scienta.2012.10.002

90. Agarwal, A., Gupta, S. D., & Barman, M. (2018). Photosynthetic apparatus plays a central role in photosensitive physiological acclimations affecting spinach (Spinacia oleracea L.) growth in response to blue and red photon flux ratios. Environmental and Experimental Botany, 156, 170-182. https://doi.org/10.1016/j.envexpbot.2018.09.009

91. Kang, J. H., KrishnaKumar, S., Atulba, S. L. S., Jeong, B. R., & Hwang, S. J. (2013). Light intensity and photoperiod influence the growth and development of hydroponically grown leaf lettuce in a closed-type plant factory system. Horticulture, Environment, and Biotechnology, 54(6), 501-509. https://doi.org/10.1007/s13580-013-0109-8

92. Kelly, N., Choe, D., Meng, Q., & Runkle, E. S. (2020). Promotion of lettuce growth under an increasing daily light integral depends on the combination of the photosynthetic photon flux density and photoperiod. Scientia Horticulturae, 272, 109565. https://doi.org/10.1016/j.scienta.2020.109565

93. Yan, Z., He, D., Niu, G., & Zhai, H. (2019). Evaluation of growth and quality of hydroponic lettuce at harvest as affected by the light intensity, photoperiod and light quality at seedling stage. Scientia Horticulturae, 248, 138-144. https://doi.org/10.1016/j.scienta.2019.01.002

94. Chen, X. L., Guo, W. Z., Xue, X. Z., Wang, L. C., & Qiao, X. J. (2014). Growth and quality responses of 'Green Oak Leaf' lettuce as affected by monochromic or mixed radiation provided by fluorescent lamp (FL) and light-emitting diode (LED). Scientia Horticulturae, 172, 168-175. https://doi.org/10.1016/j.scienta.2014.04.009

95. Zhou, C., Zhang, Y., Liu, W., Zha, L., Shao, M., & Li, B. (2020). Light intensity and leaf movement, rather than red and blue light, determine biomass accumulation and partitioning in soybean seedlings. PeerJ, 8, e8434. https://doi.org/10.7717/peerj.8434

96. Park, Y., & Runkle, E. S. (2017). Far-red radiation promotes growth of seedlings by increasing leaf expansion and whole-plant net assimilation. Environmental and Experimental Botany, 136, 41-49. https://doi.org/10.1016/j.envexpbot.2016.12.013

97. Moreno, J., Tao, Y., Chory, J., &Ballaré, C. L. (2009). A role for RFI2 in the regulation of circadian rhythms. Plant Signaling&Behavior, 4(10), 935-938. https://doi.org/10.4161/psb.4.10.9662

98. Zhen, S., & van Iersel, M. W. (2017). Far-red light is needed for efficient photochemistry and photosynthesis. Journal of Plant Physiology, 209, 115-122. https://doi.org/10.1016/j.jplph.2016.12.004

99. Zhen, S., Haidekker, M., & van Iersel, M. W. (2019). Far-red light enhances photochemical efficiency in a wavelength-dependent manner. Physiologia Plantarum, 167(1), 21-33. https://doi.org/10.1111/ppl.12834

100. Cao, K., Yu, J., Xu, D., Ai, K., Bao, E., & Zou, Z. (2018). Exposure to lower red to far-red light ratios improve tomato tolerance to salt stress. BMC Plant Biology, 18(1), 1-10. https://doi.org/10.1186/s12870-018-1310-9

101. Zou, J., Zhang, Y., Zhang, Y., Bian, Z., Fanourakis, D., Yang, Q., & Li, T. (2019). Morphological and physiological properties of indoor cultivated lettuce in response to additional far-red light. Scientia Horticulturae, 257, 108725. https://doi.org/10.1016/j.scienta.2019.108725

102. Meng, Q., & Runkle, E. S. (2019). Far-red radiation interacts with relative and absolute blue and red photon flux densities to regulate growth, morphology, and pigmentation of lettuce and basil seedlings. Scientia Horticulturae, 255, 269-280. https://doi.org/10.1016/j.scienta.2019.05.030

103. Viršilė, A., Olle, M., &Duchovskis, P. (2017). LED lighting in horticulture. In Light Emitting Diodes for Agriculture (pp. 113-147). Springer, Singapore. https://doi.org/10.1007/978-981-10-5807-3_7

104. Vaštakaitė, V., &Viršilė, A. (2015). Light-emitting diodes (LEDs) for higher nutritional quality of Brassicaceae microgreens. In Proceedings of the Annual 21st International Scientific Conference:"Research for Rural Development", Jelgava, Latvia, 13-15 May 2015; Latvia University of Agriculture: Jelgava, Latvia, 2015; Volume 1, pp. 111-117.

105. Bian, Z., Cheng, R., Wang, Y., Yang, Q., & Lu, C. (2018). Effect of green light on nitrate reduction and edible quality of hydroponically grown lettuce (Lactuca sativa L.) under short-term continuous light from red and blue light-emitting diodes. Environmental and Experimental Botany, 153, 63-71. https://doi.org/10.1016/j.envexpbot.2018.05.010

106. Smith, H. L., McAusland, L., & Murchie, E. H. (2017). Don't ignore the green light: exploring diverse roles in plant processes. Journal of Experimental Botany, 68(9), 2099-2110. https://doi.org/10.1093/jxb/erx098

107. Yano, A., & Fujiwara, K. (2012). Plant lighting system with five wavelength-band light-emitting diodes providing photon flux density and mixing ratio control. Plant Methods, 8(1), 1-12. https://doi.org/10.1186/1746-4811-8-46

108. Wu, Y., Guo, Q., Yang, F., Zhang, P., Wang, X., Wang, Y., ... & Lin, W. (2019). Supplementary green light contributes to mitigating the effects of exposure to red and blue light on plant growth and leaf pigmentation. Frontiers in Plant Science, 10, 1587. https://doi.org/10.3389/fpls.2019.01587

109. Kim, H. M., & Hwang, S. J. (2019). The growth and development of 'Mini Chal'Tomato plug seedlings grown under various wavelengths using light emitting diodes. Agronomy, 9(3), 157. https://doi.org/10.3390/agronomy9030157

110. Folta, K. M., & Maruhnich, S. A. (2007). Green light: a signal to slow down or stop. Journal of Experimental Botany, 58(12), 3099-3111. https://doi.org/10.1093/jxb/erm130

111. Lee, M. J., Son, K. H., & Oh, M. M. (2013). Growth and phenolic compounds of Lactuca sativa L. grown in a closed-type plant production system with UV-A, -B, or -C lamp.

Journal of the Science of Food and Agriculture, 93(4), 847-854. https://doi.org/10.1002/jsfa.5821

112. Li, J., Hikosaka, S., & Goto, E. (2015). Effects of light quality and photosynthetic photon flux on growth and carotenoid pigments in spinach (Spinacia oleracea L.). Acta Horticulturae, 1107, 111-116. https://doi.org/10.17660/ActaHortic.2015.1107.15

113. Su, N., Wu, Q., Shen, Z., Xia, K., & Cui, J. (2014). Effects of light quality on the chloroplastic ultrastructure and photosynthetic characteristics of cucumber seedlings. Plant Growth Regulation, 73(3), 227-235. https://doi.org/10.1007/s10725-013-9883-7

114. Kopsell, D. A., & Sams, C. E. (2013). Increases in shoot tissue pigments, glucosinolates, and mineral elements in sprouting broccoli after exposure to short-duration blue light from light emitting diodes. Journal of the American Society for Horticultural Science, 138(1), 31-37. https://doi.org/10.21273/JASHS.138.1.31

115. Brazaitytė, A., Viršilė, A., Jankauskienė, J., Sakalauskienė, S., Samuolienė, G., Sirtautas, R., ... &Duchovskis, P. (2015). Effect of supplemental UV-A irradiation in solid-state lighting on the growth and phytochemical content of microgreens. International Agrophysics, 29(1), 13-22. https://doi.org/10.1515/intag-2015-0004

116. Naznin, M. T., Lefsrud, M., Gravel, V., & Hao, X. (2016). Different ratios of red and blue LED light effects on coriander productivity and antioxidant properties. Acta Horticulturae, 1134, 223-230. https://doi.org/10.17660/ActaHortic.2016.1134.30

117. Samuolienė, G., Brazaitytė, A., Sirtautas, R., Sakalauskienė, S., Jankauskienė, J., Duchovskis, P., &Novičkovas, A. (2012). The impact of supplementary short-term red LED lighting on the antioxidant properties of microgreens. Acta Horticulturae, 956, 649-656. https://doi.org/10.17660/ActaHortic.2012.956.78

118. Agarwal, A., & Dutta Gupta, S. (2016). Impact of light-emitting diodes (LEDs) and its potential on plant growth and development in controlled-environment plant production system. Current Biotechnology, 5(1), 28-43. https://doi.org/10.2174/2211550104666151006001126

119. Yorio, N. C., Goins, G. D., Kagie, H. R., Wheeler, R. M., & Sager, J. C. (2001). Improving spinach, radish, and lettuce growth under red light-emitting diodes (LEDs) with blue light supplementation. HortScience, 36(2), 380-383. https://doi.org/10.21273/HORTSCI.36.2.380

120. Folta, K. M. (2004). Green light stimulates early stem elongation, antagonizing light-mediated growth inhibition. Plant Physiology, 135(3), 1407-1416. https://doi.org/10.1104/pp.104.038893

121. Tang, Y., Mao, R., Guo, S., Li, G., Wen, S., & Tao, Y. (2014). Overexpression of phytochrome A and its hyperactive mutant improves shade tolerance and turf quality in creeping bentgrass and zoysiagrass. Planta, 239(3), 611-623. https://doi.org/10.1007/s00425-013-1989-7

122. Nicole, C. C. S., Charalambous, F., Martinakos, S., van de Voort, S., Li, Z., Verhoog, M., & Krijn, M. (2016). Lettuce growth and quality optimization in a plant factory. Acta Horticulturae, 1134, 231-238. https://doi.org/10.17660/ActaHortic.2016.1134.31

123. Kaiser, E., Ouzounis, T., Giday, H., Schipper, R., Heuvelink, E., & Marcelis, L. F. M. (2018). Adding blue to red supplemental light increases biomass and yield of greenhouse-grown tomatoes, but only to an optimum. Frontiers in Plant Science, 9, 2002. https://doi.org/10.3389/fpls.2018.02002

124. Li, T., Heuvelink, E., van Noort, F., Kromdijk, J., & Marcelis, L. F. (2014). Responses of two Anthurium cultivars to high daily integrals of diffuse light. Scientia Horticulturae, 179, 306-313. https://doi.org/10.1016/j.scienta.2014.09.039

125. Dong, C., Fu, Y., Liu, G., & Liu, H. (2014). Low light intensity effects on the growth, photosynthetic characteristics, antioxidant capacity, yield and quality of wheat (Triticum aestivum L.) at different growth stages in BLSS. Advances in Space Research, 53(11), 1557-1566. https://doi.org/10.1016/j.asr.2014.02.004

126. Hao, X., Zhang, X., Guo, X., Little, C., & Zheng, J. (2017). Dynamic temperature control strategy with a temperature drop improves responses of greenhouse fruit vegetables to long photoperiods of supplemental lighting and saves energy. Acta Horticulturae, 1182, 185-192. https://doi.org/10.17660/ActaHortic.2017.1182.24

127. Jin, W., Urbina, J. L., Heuvelink, E., & Marcelis, L. F. (2018). Adding far-red to red-blue light-emitting diode light promotes yield of lettuce at different planting densities. Frontiers in Plant Science, 9, 1110. https://doi.org/10.3389/fpls.2018.01110

128. Zhang, G., Shen, S., Takagaki, M., Kozai, T., & Yamori, W. (2015). Supplemental upward lighting from underneath to obtain higher marketable lettuce (Lactuca sativa) leaf fresh weight by retarding senescence of outer leaves. Frontiers in Plant Science, 6, 1110. https://doi.org/10.3389/fpls.2015.01110

129. Snowden, M. C., Cope, K. R., & Bugbee, B. (2016). Sensitivity of seven diverse species to blue and green light: interactions with photon flux. PLoS One, 11(10), e0163121. https://doi.org/10.1371/journal.pone.0163121

130. McCree, K. J. (1972). The action spectrum, absorptance and quantum yield of photosynthesis in crop plants. Agricultural Meteorology, 9, 191-216. https://doi.org/10.1016/0002-1571(71)90022-7

131. Inada, K. (1976). Action spectra for photosynthesis in higher plants. Plant and Cell Physiology, 17(2), 355-365. https://doi.org/10.1093/oxfordjournals.pcp.a075288

132. Wheeler, R. M., Mackowiak, C. L., Sager, J. C., Knott, W. M., & Berry, W. L. (1994). Growth of soybean and potato at high CO2 partial pressures. Advances in Space Research, 14(11), 251-255. https://doi.org/10.1016/0273-1177(94)90303-4

133. Gómez, C., & Izzo, L. G. (2018). Increasing efficiency of crop production with LEDs. AIMS Agriculture and Food, 3(2), 135-153. https://doi.org/10.3934/agrfood.2018.2.135

134. Pennisi, G., Blasioli, S., Cellini, A., Maia, L., Crepaldi, A., Braschi, I., ... & Gianquinto, G. (2019). Unraveling the role of red: blue LED lights on resource use efficiency and nutritional properties of indoor grown sweet basil. Frontiers in Plant Science, 10, 305. https://doi.org/10.3389/fpls.2019.00305