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Vertical farming: A sustainable agriculture format of the future

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Abstract
With a burgeoning global population and diminishing agricultural land per capita, the urgency to meet escalating food demands while confronting challenges like climate change, soil fertility loss, and water scarcity has sparked interest in alternative farming methods. Vertical farming emerges as a promising solution, this review article explores the background, necessity, types, and advantages of vertical farming, focusing on hydroponics, aeroponics, and aquaponics. These methods offer water efficiency, space optimization, year-round cultivation, mitigating climate-related risks and reducing reliance on herbicides and pesticides. Despite limitations in research and skilled resources, vertical farming in India promises high yield and sustainability. Emphasizing technological advancements, scaling up, refined local methods, and government support becomes pivotal for its economic viability and widespread adoption. Robust research and strategic investments are essential to foster innovation and enable farmers to embrace this transformative agricultural approach.

Keywords: Vertical farming, hydroponics, aeroponics, aquaponics

Introduction
As the global population continues to surge and urbanization transforms landscapes, traditional agriculture is confronted with unprecedented challenges. Currently, with a global population of 8 billion, the per capita availability of agricultural land stands at 0.29 hectares, and is projected to decrease to 0.16 ha by 2050 (Zhu, 2023) [43]. In India, this figure is presently at 0.12 ha. Roughly 800 mha of land worldwide is allocated to soil-based farming, making up about 38% of the world's total land area. The world is on the brink of population explosion, estimated to reach 9.8 billion by 2050. Meeting the increasing food demands due to burgeoning populations and shifting diets is becoming more challenging as agricultural production rates are expected to plateau in the 21st century (Ray *et al*., 2012) [32]. Factors like rapid urbanization, natural disasters, climate change, and excessive use of chemicals and pesticides have negatively impacted soil fertility. Challenges such as changing climate patterns, rising temperatures and irregular weather patterns further exacerbate the situation. These issues pose a severe threat to traditional soil-based agricultural systems, making the task of producing food extremely difficult. To address this, more efficient and eco-friendly modern farming methods need to supplement conventional soil-based practices (Lambin & Meyfroidt, 2011) [23]. One of the most promising alternatives to soil-based farming is vertical farming techniques, which could potentially complement existing systems and mitigate the scarcity of fertile arable lands and water resources.
Vertical farming represents a paradigm shift in how we cultivate crops, departing from conventional methods often constrained by limited arable land, seasonal changes, and reliance on external factors such as climate conditions (Passador & Lombardi Jr, 2022) [28].
The core principle of vertical farming revolves around maximizing the use of vertical space, typically through multi-storeyed structures or inclined surfaces, to accommodate multiple layers of crops. The implementation of Controlled Environment Agriculture (CEA), which entails precisely regulating environmental elements like temperature, humidity, and light to generate ideal conditions for plant development, complements this spatial efficiency. To increase productivity and efficiency per square foot, vertical farming involves growing and producing

crops and plants on surfaces that are vertically inclined and layered (Barui *et al*., 2022) [6]. Production-related variables like temperature, lighting, fertilizers, watering, and air circulation are continuously monitored and modified. Technologies like hydroponics, aeroponics, and aquaponics further contribute to resource efficiency by delivering nutrients directly to plants. The incorporation of cutting-edge technologies is a hallmark of vertical farming, with advancements in LED lighting, automated climate control systems, robotics, and artificial intelligence transforming the cultivation process. These technologies make it possible to produce all year round, regardless of the outside weather, and they make it easier to precisely control the elements that are essential to the growth of plants. The combination of cutting-edge technology and creative farming techniques establishes vertical farming as a viable substitute for conventional agriculture (Paucek *et al*., 2023) [29].

This review aims to explore the multifaceted dimensions of vertical farming, ranging from its
fundamental principles and technological underpinnings to its environmental impacts, economic feasibility, and potential contributions to food security (Meemken & Qaim, 2018) [25]. By critically evaluating the advantages and challenges associated with vertical farming, we aim to provide a comprehensive understanding of its role in shaping the future of agriculture.

Background of Vertical Farming

Gilbert Ellis Bailey wrote a book named "Vertical Farming" and created the phrase "vertical farming" in 1915. At the University of California at Berkley, William Frederick Gericke invented hydroponics in the early 1930s. In 1999, Professor Dickson Despommier introduced the concept of vertical farming, aiming to cultivate food directly within urban areas. His idea was to minimize transportation distance and time by growing food close to cities. This approach sought to provide fresher produce more quickly and at reduced costs by establishing food production within urban environments (Al-Kodmany, 2018) [1]. The notion of vertical farming has garnered significant attention in recent times as a reaction to the obstacles presented by conventional agriculture, including the lack of water, the restricted amount of arable land, and the ecological consequences of these activities (Rahmann *et al*., 2021) [31]. The idea of growing crops in stacked layers dates back to ancient times, with historical examples like the Hanging Gardens of Babylon. However, the modern concept of vertical farming emerged in the early 21st century, propelled by advancements in technology, agriculture, and sustainability (Al-Kodmany, 2018) [1].

Principles of Vertical Farming

Vertical farming is an innovative and sustainable agricultural practice with the principle rooted in addressing various challenges associated with traditional agriculture and promoting efficiency, resource conservation, and increased food production. Vertical farming maximizes the use of vertical space, allowing for the cultivation of crops in stacked layers. Due to its ability to produce more crops per square meter than traditional horizontal farming, this method is appropriate for urban areas with limited land (Bunge *et al*., 2022; Giurgiu *et al*., 2015) [10,17]. Vertical farms aim to optimize resource use, including water, nutrients, and energy. Controlled environments, such as hydroponics or aeroponics systems, minimize water usage by delivering nutrients directly to plants' roots. Additionally, energy-efficient lighting and climate control systems help conserve energy. Vertical farming provides the opportunity for year-round cultivation, independent of external weather conditions. With controlled environments, crops can be grown consistently, reducing seasonal limitations and enhancing overall productivity. It minimizes the need for large expanses of land, decreases water usage, and lowers the reliance on pesticides and herbicides (Jacquet *et al*., 2022) [19]. Vertical farming can be implemented in urban areas, bringing agriculture closer to consumers. Localized production also promotes fresher and more nutrient-rich produce. With controlled environments, vertical farming can help protect crops from pests and diseases. This reduces the reliance on chemical pesticides, contributing to preserving biodiversity and the overall health of ecosystems (Cárceles *et al*., 2022) [12]. Vertical farming heavily relies on advanced technologies such as LED lighting, sensors, automation, and data analytics. These technologies enable precise control over environmental conditions, optimizing plant growth and resource utilization. Vertical farming initiatives often involve community engagement and education. This promotes understanding of food production, sustainable farming methods, and the value of wholesome, locally sourced food (Paucek *et al*., 2023) [29].

Types of Vertical Farming

Controlled Environment Agriculture

Controlled Environment Agriculture (CEA) refers to the practice of growing crops in an environment that is tightly controlled to optimize various growth factors such as temperature, CO_2 levels, humidity, and light. Vertical farming, a form of CEA, involves stacking layers of crops inside a regulated indoor setting, often in vertical towers or shelves. CEA allows for year-round cultivation, overcoming seasonal limitations. This continuous production can contribute to a more consistent and reliable food supply. By controlling environmental variables, CEA minimizes resource wastage, such as water and fertilizers, and mitigates the impact of adverse weather conditions, pests, and diseases, providing a more stable and predictable growing environment. Climate control systems play a crucial role in CEA, affecting crop yields significantly. Maintaining CO_2 levels, optimal temperature, and humidity can positively impact plant growth and productivity with the use of sophisticated sensors, computer-controlled systems, and feedback mechanisms. With the use of these technologies, plant growth environments can be stabilized and improved, producing higher yields and higher-quality products. (Engler & Krarti, 2021; Nelkin & Caplow, 2008) [14,27]. In CEA, artificial lighting systems are essential, particularly in interior spaces where natural sunlight may be scarce. LED lights are more energy-efficient, producing less heat and consuming less electricity compared to traditional lighting systems. LED technology allows for precise control over the light spectrum, enabling growers to tailor the light conditions to the specific needs of different crops. This optimization can enhance photosynthesis and overall plant growth. Automation technologies are employed in the execution of operations like maintenance, harvesting, and planting. This reduces the need for manual labor, lowers production costs, and enhances overall efficiency (Passador & Lombardi, 2022) [28]. Internet of Things (IoT) sensors are employed for real-time monitoring of environmental conditions, allowing growers to make data-driven decisions. These sensors provide valuable insights into factors like temperature, humidity, soil moisture, and nutrient levels. Automation and IoT integration contribute to resource efficiency by optimizing the use of water, fertilizers, and energy. In conclusion, the integration of controlled environments, advanced climate control systems, artificial lighting, and automation technologies in CEA represents a significant advancement in agriculture, offering solutions to challenges related to resource constraints and climate variability (Benke & Tomkins, 2017; Wang *et al*., 2023) [8, 40].

Hydroponics

Growing plants without soil is referred to as "hydroponics"(Figure 1). In hydroponic systems, liquid nutrient solutions containing macro- and micronutrients are submerged in the roots of plants. In addition, inert (chemically inactive) media are used as soil substitutes to assist the roots. These include gravel, sand, sawdust, perlite, vermiculite, coconut coir, rock wool, and clay pellets. Compared to conventional soil-based farming, this method has several benefits, such as more exact control over nutrient levels, and water use, a decrease in the requirement for pesticides and herbicides, and enhanced environmental conditions. A study found that while hydroponic farming uses 13 times less water than traditional farming, it may produce lettuce with an approximately 11-fold increase in yield per area. Along with being widely utilized for producing some fruit crops, vegetables, and herbs, hydroponics is becoming more and more well-liked in the cannabis growing sector (Barbosa *et al*., 2015; Zhang *et al*., 2022) [5, 42].

Fig 1: Hydroponically grown plants

Aeroponics

NASA (National Aeronautical and Space Administration) wanted to establish an effective way to grow plants in space, and this goal led to the development of aeroponics. The Latin words "aero" (air) and "ponic" (work) are the roots of the term "aeroponic." The plants are kept floating in nutrient-rich liquid solutions in air chambers. Aeroponics is by far the most environmentally friendly soilless growing technique, requiring up to 90% less water and no need to replace the growing media (Farran & Mingo-Castel, 2006) [15]. Water-strapped places are perfect for it. Aeroponic's improved aeration, which enables the plant's stem and root systems to absorb all of the oxygen in the air and so promotes root growth, is one of its key advantages. Rapid crop growth is achieved with 70% less water used than with hydroponics. The most water-efficient method is aeroponics, which doesn't require changing the growth medium. Moreover, studies have demonstrated that using this high-density planting technique increases yields and facilitates harvesting. Because gravity naturally reduces excess liquid in aeroponic systems, as compared with standard hydroponic systems that frequently require water pumps to manage excess solution, aeroponic systems may also be constructed vertically, which further saves energy use. This is because a growth substrate isn't required in aeroponic systems *(*Bucking *et al*., *2012;* Lakhiar *et al*., 2018) [9, 22]. According to the CIP 2008 research, a single potato plant can yield over 100 mini tubers in a single row, in contrast to the typical method that uses soil in a greenhouse to generate about 5 to 6 tubers per plant in 90 days. For a year, the conventional approach yields only 8 daughter tubers. According to Farran *et al*. (2006) [15] weekly harvests during five months with a mini tuber yield of 800 tubers/m^2 at a plant density of 60 plants/m^2.

Aquaponics

The words aquaculture, which refers to rearing fish, and hydroponics, which refers to growing plants without soil, are combined to form the term aquaponics. Aquaponics is the advancement of hydroponics by fusing the culture of aquatic organisms with that of terrestrial plants in a closed-loop system that mimics nature. Nutrient-rich effluent from the fish tanks is filtered by a solid removal unit and sent to a bio-filter, where poisonous ammonia is changed into nutrient-rich nitrate. As the plants take up nutrients, the effluent is filtered and recycled back into the fish tanks (Figure 2). Moreover, the water in the fish tanks absorbs heat and the plants absorb the carbon dioxide that the fish release, helping to regulate the greenhouse's nighttime temperature and save electricity. To maintain the health of the fish and plants in the system, aquaponics involves regular monitoring and management of water quality, temperature, and other variables. However, it also offers several benefits, including environmental sustainability, effective use of space, and a decreased need for chemical fertilizers. It is a sustainable and innovative approach to food production that has gained popularity in recent years (Goddek *et al*., 2019; Shafahi & Woolston, 2014) [18, 35].

Fig 2: Aquaponics

Case Studies

Table 1: Analyzing effective case studies provides insightful information about the real-world use and results of vertical farming projects. Here are a few illustrative examples

No.	Project Name	Country	Methods
1	Future Farms	(Bangalore), India	Future Farms is a vertical farming company, focusing on sustainable and tech-driven agriculture. The company employs hydroponics and precision agriculture techniques to optimize resource use and crop yields. Future Farms aims to provide fresh, locally-grown produce to urban consumers and support local agriculture.
2	Urban Kisaan	(Hyderabad), India	Urban Kisaan is an urban farming startup with vertical farms, emphasizing the importance of growing food within the city. The business ensures year-round production by using vertical hydroponic systems to cultivate a range of crops in a regulated atmosphere. It focuses on community engagement, educating residents about sustainable farming practices, and promoting the consumption of locally grown, pesticide-free produce.
3	Aeroponic Farms	(IIT Kharagpur), India	IIT Kharagpur has been involved in the research and implementation of aeroponic farming systems. They are engaged in research and development to explore the feasibility and scalability of these methods. These academic initiatives provide opportunities for collaboration between educational institutions and the agricultural industry to advance the understanding and application of vertical farming in India.
4	AeroFarms	United States	AeroFarms, situated in Newark, New Jersey, is a vertical farming company that has garnered attention for its innovative approach. Utilizing aeroponic systems and LED lighting, Aero Farms grows a variety of leafy greens, herbs, and microgreens in vertically stacked layers. The company repurposed a former steel factory, demonstrating the adaptability of vertical farming to urban environments.
5	Sky Greens	Singapore	Singapore, a city-state with limited land availability, faces challenges in food production. Sky Greens addresses this by implementing vertical farming techniques in the form of A-Go-Gro vertical farming towers. These rotating towers allow crops to receive sunlight and water evenly. To improve food security and lessen dependency on food imports, Singapore has benefited from Sky Greens' demonstration of the viability of vertical farming in crowded urban settings.
6	Vertical Harvest	United States	Located in Jackson, Wyoming, Vertical Harvest is an exemplary case of vertical farming in a small urban setting. This three-story vertical greenhouse operates year-round, producing a variety of crops, including tomatoes, herbs, and greens employing individuals with disabilities.
7	Plantagon	Sweden	Plantagon, headquartered in Sweden, focuses on developing vertical farming solutions for urban agriculture. Their flagship project, the Plantagon City Farm in Linköping, integrates a vertical greenhouse with office space. This innovative concept combines food production with urban infrastructure, demonstrating the potential for multifunctional urban spaces.
8	Spread Co.	Japan	Spread Co., based in Kyoto, Japan, operates the world's first robot-run farm, known as the Vegetable Factory. This vertical farm utilizes automation and robotics to handle tasks such as planting, harvesting, and packaging. The controlled environment allows for precision farming, ensuring optimal conditions for crop growth. Spread Co.'s approach highlights the role of technology in increasing efficiency and reducing labor costs in vertical farming.
9	Jones Food Company	United Kingdom	Jones Food Company operates one of Europe's largest vertical farms in Scunthorpe, UK. This facility spans 5,120 square meters and utilizes hydroponic systems and LED lighting. The scale of this operation showcases the potential for large-scale vertical farming to meet the demand for fresh produce. Jones Food Company emphasizes the reduction of food miles and the ability to provide local, sustainable food to the surrounding community.
10	Freight Farms	Global	Freight Farms offers a unique approach to vertical farming through its shipping container farms, known as Leafy Green Machines (LGMs). These portable, hydroponic farms are designed to be placed in various urban settings. The modularity and mobility of Freight Farms' solutions enable farmers to set up vertical farms in unconventional spaces, contributing to the adaptability of vertical farming in diverse environments.

These case studies highlight the diversity of vertical farming applications, from repurposing industrial spaces to integrating with urban infrastructure and employing advanced automation. Each case study provides a unique perspective on how vertical farming can be tailored to specific geographic, economic, and social contexts, emphasizing the versatility and adaptability of this agricultural approach. The successful implementation of these projects showcases the potential of vertical farming in addressing global challenges related to food security, resource efficiency, and sustainable urban development (Jaeger *et al*., 2022; Sandison *et al*., 2023; Wang *et al*., 2023) [20, 33, 40].

Environmental Impacts and Sustainability

Vertical farming offers a range of potential benefits that address some of the critical ecological concerns associated with traditional agriculture.

1. **Space Efficiency:** Vertical farming, utilizes space more efficiently by stacking crops in multiple layers or vertically inclined structures. Compared to conventional horizontal farming, this enables a larger crop output per square foot, which makes it the perfect option for highly populated metropolitan regions with limited space (Specht *et al*., 2014; Tablada *et al*., 2020) [37, 38].
2. **Water Conservation:** Water scarcity is anticipated to worsen as temperatures rise and droughts become more frequent. Contrarily, vertical farming conserves up to 90% of the water needed for cultivating the same crop while also providing higher yields in comparison to traditional agriculture. When compared to conventional soil-based agriculture, hydroponic systems consume up to 70% less water. Continuous recirculation and reuse of water mitigate shortages, offering a more eco-friendly solution, particularly beneficial in water-scarce regions (Mir *et al*., 2022; Sivamani *et al*., 2014) [26, 36].
3. **Reduced Pesticide Use:** Pesticides can have negative impacts on ecosystems and human health, but the controlled environment of vertical farms reduces the risk of pests and diseases. Vertical farming's emphasis on clean, controlled conditions contributes to the production of healthier, pesticide-free crops, aligning with environmentally conscious farming practices (Jacquet *et al*., 2022) [19].
4. **Energy Efficiency:** To provide the best growing

circumstances, vertical farms use energy-efficient technologies like sophisticated climate control systems and LED lighting. While there is an initial energy investment, precise control of environmental variables can outweigh the environmental impact. Moreover, continuous attempts to integrate renewable energy sources, such as solar or wind power, are meant to further increase the energy sustainability of vertical farming (Engler & Krarti, 2021) [14].

5. **Carbon Emission Reduction:** Localized vertical farms minimize the amount of carbon emissions from transportation by reducing the distance food must travel from the farm to the consumer, especially when they are incorporated into metropolitan areas. Thus, vertical farming contributes to an environment-friendly food distribution system and mitigates climate change issues (Barange *et al*., 2018) [4].
6. **Year-Round Production:** Traditional agriculture often relies on seasonal cycles, leading to periods of crop scarcity. With its year-round operation, vertical farming guarantees a steady and dependable supply of fresh produce, negating the need for protracted storage and transit procedures that worsen the environment, particularly when it comes to perishable commodities. This consistent production contributes to food security by ensuring a steady supply of fresh produce (Sandison *et al*., 2023; Specht *et al*., 2014) [33, 37].
7. **Biodiversity Preservation:** Vertical farming's efficient use of space converts the expansion of agricultural land into natural ecosystems. By minimizing land clearing, it contributes to the preservation of biodiversity and protects wildlife habitats that support ecological balance and conservation efforts. (Cappelli *et al*., 2022; Lin *et al*., 2015) [11, 24].
8. **Crop Stacking and Diversity:** A wide variety of crops can be grown simultaneously in the same area by stacking them vertically. This diversity enhances nutritional variety and addresses food security concerns by providing a broader spectrum of nutrients to consumers (Bach *et al*., 2020) [3].
9. **Job Creation:** Vertical farming presents employment opportunities in various fields like data analysis, research, food science, etc., contributing to the evolution of workforce skill sets.

However, it's crucial to acknowledge potential challenges and unintended consequences. Nevertheless, when implemented thoughtfully, vertical farming stands as a promising model for sustainable agriculture, offering a pathway to reconcile global food demand with environmental conservation.

Indian perspective on vertical farming: Vertical farming in India faces cost challenges hindering competitive market pricing. Yet, it thrives in metros, primarily in soilless farms owned by hotels, supplying top-tier produce. However, skilled human resources are nascent, posing limitations on its expansion. Despite hurdles, it promises high yields, sustainability, and potential market integration.

Economic Feasibility

Several factors contribute to the economic feasibility of vertical farming, ranging from initial setup costs to ongoing operational expenses and potential returns on investment.

1. **Initial Investment:** One of the primary challenges for prospective vertical farmers is the initial capital investment. Constructing or retrofitting facilities for vertical farming, acquiring advanced technologies (such as LED lighting, automated systems, and environmental controls), and implementing hydroponic or aeroponic systems can incur significant upfront costs. The scale and scope of the vertical farm, as well as the chosen technologies, will heavily influence these initial expenses (Van Gerrewey *et al*., 2021) [39].
2. **Operational Costs:** Beyond the initial investment, ongoing operational costs include expenditures on electricity, water, nutrients, labor, and maintenance. The cost of energy, particularly associated with lighting and climate control, can constitute a significant portion of operational expenses. Advances in energy-efficient technologies and the integration of renewable energy sources can help mitigate these ongoing costs (Chable *et al*., 2020; Van Gerrewey *et al*., 2021) [13, 39].
3. **Crop Yields and Revenue Generation:** The economic feasibility of vertical farming is closely tied to the ability to achieve consistent and high crop yields. The ability to produce crops year-round and in urban environments may enable vertical farmers to cater to consistent demand, potentially resulting in higher revenue generation (Santini *et al*., 2021) [34].
4. **Technological Complexity:** The integration of advanced technologies, while beneficial, can introduce complexity. Adequate training and maintenance are crucial for ensuring the smooth operation of high-tech vertical farming systems. The primary urban water supply may be disrupted and contaminated by the excess fertilizers used in vertical farming if they are not appropriately handled (Jagadeesh, 2021) [21].
5. **Market Demand and Pricing:** Consumer preferences for fresh and pesticide-free products can drive demand for vertical farm produce. However, pricing strategies must be competitive with traditional agriculture to secure market share (Perambalam *et al*., 2021) [30].
6. **Economies of Scale:** As vertical farming operations scale up, there is the potential for economies of scale to come into play. Larger operations may benefit from cost reductions in areas such as technology acquisition, bulk purchasing of inputs, and more efficient use of resources. However, achieving economies of scale requires careful planning and management (Van Gerrewey *et al*., 2021) [39].
7. **Environmental Impact of Production Materials:** The production of materials such as LED lights, sensors, and other high-tech equipment may have environmental impacts. LED lighting systems, despite emitting minimal heat, could pose challenges in temperature regulation, particularly during the Summer months. The energy-intensive nature of vertical farming, particularly due to artificial lighting and climate control, contributes to significant energy consumption. Balancing productivity with energy efficiency and exploring renewable energy sources are ongoing challenges (Engler & Krarti, 2021; Lakhiar *et al*., 2018) [14, 22].
8. **Research and Development:** Ongoing research and development in vertical farming technologies can contribute to cost reductions over time. Innovations in energy-efficient lighting, automation, and cultivation techniques have the potential to enhance productivity and reduce operational expenses, ultimately improving the economic feasibility of vertical farming (Ghazal *et al*., 2023) [16].
9. **Private Investment and Funding:** Venture finance and private investors are essential to the expansion of vertical

farming. Funding from private sources can enable technology development, facility construction, and operational expansion. The confidence of investors in the economic viability of vertical farming can drive further innovation and industry growth (Van Gerrewey *et al*., 2021) [39].

In conclusion, while the initial costs of vertical farming can be substantial, ongoing advancements in technology, favorable market conditions, government support, and economies of scale have the potential to enhance its economic feasibility. As the industry matures and becomes more established, the economic landscape will likely evolve, making vertical farming an increasingly viable and competitive alternative to traditional agriculture.

Food Security and Urban Agriculture

There is great potential for vertical farming to improve food security, especially when combined with urban agriculture. The intersection of these two concepts addresses the challenges associated with a rapidly urbanizing world and the need to sustainably meet the nutritional demands of growing an urban population.

1. Localized food production close to cities lessens reliance on long-distance transit, resulting in a more adaptable and robust food supply chain that supports economical and effective food distribution (Yuan *et al*., 2022) [41]. It ensures that fresh produce is readily available for consumption, mitigating the potential disruptions associated with transport logistics or external environmental factors (Santini *et al*., 2021) [34].
2. Urban agriculture, including community-supported vertical farming initiatives, fosters community engagement and education. Residents become more connected to the food production process, gain a better understanding of sustainable agricultural practices, and develop a sense of food security. Community involvement in vertical farming can create resilient, self-sustaining urban food systems (Ghazal *et al*., 2023) [16].
3. A wide variety of crops can be grown vertically in a comparatively small area. This diversification reduces reliance on a limited set of traditional crops and promotes the cultivation of a broader spectrum of fruits, vegetables, and herbs, enhancing food security by ensuring a variety of nutrient sources (Avgoustaki & Xydis, 2020) [2].
4. Food deserts are sections of urban areas where people have limited access to wholesome, fresh food. In these locations, vertical farming can be deliberately developed to offer a nearby and easily accessible source of nutrient-dense vegetables (Bellian, 2019) [7].
5. Urban vertical farms, incorporating advanced irrigation methods like hydroponics or aeroponics, demonstrate high water use efficiency. This environmentally conscious approach contributes to sustainable urban agriculture, ensuring that water resources are used judiciously (Mir *et al*., 2022; Sivamani *et al*., 2014) [26,436].

Conclusion

The future of vertical farming holds immense potential, but several avenues require focused research to address existing challenges and unlock further opportunities. Reducing the energy footprint of vertical farms requires ongoing developments in energy-efficient technologies, such as enhanced climate control systems and LED lighting. Additionally, exploring ways to enhance crop diversity and expand the range of cultivable crops in vertical farms is essential for meeting diverse nutritional needs. Collaborative efforts between academia, industry, and policymakers can further investigate the economic and social impacts of vertical farming, ensuring its integration into global and local agricultural systems. Research in automation and artificial intelligence for precise monitoring and control within vertical farms is pivotal for operational efficiency. Finally, studies examining the long-term environmental sustainability and life cycle analysis of vertical farming systems will provide comprehensive insights, guiding the industry toward a more resilient and ecologically responsible future. In conclusion, vertical farming emerges as a transformative and sustainable approach to agriculture, offering solutions to challenges posed by urbanization, climate change, and global food demand. The advantages, ranging from space efficiency and resource optimization to localized production and reduced environmental impact, underscore its potential to reshape the future of farming. The potential of vertical farming lies in its ability to meet the needs of an expanding global population in a way that is economically feasible, socially just, and environmentally conscious. These benefits will come from technological advancements, increased public acceptance, and a dedication to environmental stewardship (Bunge *et al*., 2022) [10]. The journey toward a more sustainable future in agriculture requires continuous exploration, adaptation, and a collective commitment to foster innovation in vertical farming.

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