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Recent developments and inventive approaches in vertical farming

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"Biomimicry" is an acronym used to describe how people looked at nature for inspiration to tackle a variety of problems. The modern problems of fast-increasing urbanization, land degradation, climate change, pandemics, loss of biodiversity, and widespread use of pesticides and fertilizers seriously threaten our food supply chain. There is a growing consumer demand for nutrient-dense, flavourful plant-based cuisine with minimal environmental impact. Moreover, a considerable portion of food roughly 24% is lost before it reaches consumers, partly as a result of poor quality and protracted supply chains. Researching new methods of producing food is essential since, by 2050, there will be more than 9.7 billion people on the planet, 70% of whom will reside in cities. Vertical farming (VF), which relieves pressure on conventional agricultural land by using vertical space instead of horizontal expansion, is growing in popularity as a solution to these problems. Because VF incorporates soil-less growth techniques, it is well-suited for urban environments. This strategy may help to produce more premium products, such as fruits, vegetables, flowers, and herbs. It may also help to produce cosmetics and medications made from plants. Vertical farming, is becoming more favoured as an alternative to traditional agriculture, and provides avenues for enhancing sustainable food production given the growing challenges of climate change and population growth.

KEYWORDS
vertical farming, types of vertical farming, sensors, drones, robots

Introduction

Global warming, unchecked pesticide and chemical use, natural disasters, and fast urbanization have all had a deleterious effect on soil fertility. In addition, the amount of land available to each individual has decreased, and soil productivity and fertility have declined significantly (Lambin, 2012; Lal, 2015; Lehman et al., 2015). Concerns about uncontrolled groundwater levels, overuse of irrigation, and uncontrolled water contamination are among the causes threatening the watershed's water resources (Bhanja et al., 2018). Over 9.7 billion people are predicted to live on the earth by 2050, which means that 50% more food must be produced globally. It will require more arable land for this, but there just is not enough of it (FAO, 2016). It is predicted that by 2050, the amount of arable land per person will be less than 0.20 hectares, or less than one-third of what it was in 1970 (Conforti, 2011; FAO, 2016). The conventional soil-based agricultural production techniques are seriously threatened by these problems, which makes the current state of food production quite challenging. Soil-based farming techniques need to be supplemented with modern, environmentally friendlier, and more productive farming technologies (Lambin and Meyfroidt, 2011). Soilless production methods, including hydroponics, aquaponics, and vertical farming, offer a potential solution to contemporary agricultural issues such as declining soil fertility, exhausted nutrient stocks, restricted access to irrigation water, and the effects of climate change (Albadwawi et al., 2022). These innovations can improve water and space conservation, open up urban areas for food production, and protect water resources (Sengupta and Banerjee, 2012; Fussy and Papenbrock, 2022). However, many variables, including soil type, terrain, climate, production scale, technological sophistication, and socioeconomic standing, affect how efficient these systems are (Obalum et al., 2011). Water is conserved and year-round food production is made possible by soilless culture methods like hydroponics and aeroponics in vertical farming (Gokul and Sheeja, 2016). While much attention has been focused on high-value crops, new research has shown that staple crops can be produced with far higher yields (Zhu and Marcelis, 2023). Vertical microgreen farming is a resource- and space-efficient method that promotes global food security (Rajan et al., 2019). Vertical farming methods could offer a different approach to addressing the present scarcity of arable land and water supplies (Benke and Tomkins, 2017) and provide a possible remedy for vulnerable urban communities since it can also solve global food shortages and environmental issues (Besthorn, 2013). This review focuses on cutting-edge methods and technology as it explores the most recent developments in vertical farming.

Vertical farming: a brief history

Vertical farming has its origins in the Babylonian period, exemplified by the Hanging Gardens, which were considered one of the Seven Wonders of the Ancient World by Greek civilization and date back to 600 BC (Al-Kodmany, 2018b). Life magazine published a full-page caricature of A.B. Walker in 1909. The cartoon depicts the open construction of a skyscraper with homes stacked one on top of the other against a rural background as an advertisement for a fictional real estate company. Architecture has been greatly influenced by illustration (Van Gerrewey et al., 2021). This served as the basis for Rem Koolhaas's 1978 full-length novel Crazy New York. According to Koolhaas, this represents a theorem outlining the perfect characteristics of skyscrapers (Koolhaas, 2014). William Gericke's book The Complete Guide to Soilless Gardening, published in the 1930s, set the framework for soilless cultivation. This book rose to prominence in the chronicles of vertical farming.

The term "vertical farming" took on a completely new meaning when geologist Gilbert Ellis Bailey used explosives for the first time in 1915 to achieve depth of root development and suggested tilling the earth more deeply (Bailey, 1915; Jackson, 2023). To ensure future food security, vertical farming the practice of cultivating crops in layers that are stacked vertically is essential (Kalantari et al., 2017). It has many advantages, such as increased nutrient and water efficiency, less pesticide and herbicide use, and less agricultural pollution (Zhu and Marcelis, 2023). With a yield that might be 70–80 times greater than that of normal farmland, it has the potential to greatly increase food production (Maurya P. et al., 2023; Zhu and Marcelis, 2023). Perceived sustainability influences consumer acceptability of vertical farming methods; larger systems are thought to be more sustainable (Jürkenbeck et al., 2019). Vertical farming is anticipated to be heavily reliant on technology-driven systems like the Internet of Things (IoT) in the future, although climate control and artificial lighting have substantial energy costs (Debdas et al., 2023; Ullah et al., 2023). Vertical farming is defined in various ways depending on factors such as size, density, layout, building type, location, level of control, and intended purpose. Consequently, stakeholders may perceive vertical farming as anywhere from a minor crop production method to a critical system necessary for ensuring future food security (Maurya P. et al., 2023; Taher Abdelfatah and Mahmoud El-Arnaouty, 2023; Zhu and Marcelis, 2023).

Vertical farming includes various growth systems that vary in scale, users, technologies, locations, and objectives. It is especially well-suited for growing horticultural crops like leafy vegetables (Agrilyst, 2017). The fundamental idea behind "vertical farming" is cultivating plants on several levels to increase yield in a constrained amount of area. Regarding the phrase "vertical farm," it refers to a meticulously regulated indoor plant cultivation technique, as stated by SharathKumar et al. (2020) (or) an intricately designed indoor plant system that can produce fresh, high-quality produce all year round by carefully controlling every element of plant growth, such as temperature, light, CO2 concentration, humidity, water, and nutrients. Due to its independence from solar radiation and other environmental influences, this technology offers total control over the growing environment for the plant (Nair et al., 2017; SharathKumar et al., 2020).

Vertical farms are separated based on their size and intended use

A dedicated building houses the industrial-scale vertical farm known as Plant Factory with Artificial Lighting (PFAL) (Wang et al., 2023). A modular vertical farm housed inside a shipping container is known as a container farm (Rivero and Salvi, 2023). An indoor farm, or "in-store farm," is a vertical farm situated in a retail or restaurant setting (Zhu and Marcelis, 2023). A vertical farm appliance fitted into a house or workplace is called an appliance farm (Maurya P. et al., 2023) (see Table 1).

The necessity of vertical farming

Food security

Global food security is vital in addressing the issue of food security worldwide. It ensures that all individuals have access to safe, nutritious, and affordable food. The impact of food security extends to various areas such as health, economic development, and social stability. Lack of access to adequate food can lead to malnutrition and other health issues, hindering the overall well-being of a population (Farms.com, 2016). Land use specialists including geologists, ecologists, and agronomists note a growing scarcity of farmland (Corvalan et al., 2005; Thomaier et al., 2015). The decreasing availability of traditional farmland is primarily due to factors such as urbanization, soil degradation, and climate change. These factors are

TABLE 1 Different types of vegetation and materials required for various kinds of vertical gardens (Yu-Peng, 2010).

Vertical garden type	Suitable plants	Growing media	Construction type	References
Rock climbing	Climbing vegetation	Either in a planter box or on the ground	Very little structural support is required.	Yu-Peng (2010)
Hanging down	Plants with long stems that dangle down	Each floor has a soil planted box.	Building a planter box and its supporting framework in accordance with storey	Bailey (1915); Despommier (2013)
Modular	Short plants	Artificial growth media panel that is lightweight	Facades should be constructed with structural support for hanging or positioning modules.	Bailey (1915); Agrilyst (2017)

impacting the ability to meet the growing food demand by shrinking the area available for food production (Lehman et al., 2015). As a result, there is increased pressure on the existing farmland to produce more food, leading to overuse and decreased soil fertility.

Vertical farming offers a feasible substitute by maximizing food output in a limited space (Touliatos et al., 2016). It is predicated on the idea of creating small, self-sufficient ecosystems that can perform a range of functions, including waste management and food production (Kalantari et al., 2017). In vertical farms, controlled settings lessen the effects of pests, runoff, nutritional deficits, contaminated water, and dust on crop cultivation. Furthermore, the establishment of vertical farming could contribute to the creation of much-needed "green collar" jobs in urban areas (Healy and Rosenberg, 2013).

Low crop yields in traditional agriculture

Traditional agriculture has been the backbone of food production for centuries, but it also comes with its environmental challenges. The environmental impact of traditional agriculture is a growing concern as it contributes to deforestation, soil erosion, water pollution, and greenhouse gas emissions (Rosenzweig et al., 2014). Low crop yields are a persistent problem for traditional agriculture, which can have a big influence on farmers' income and productivity (Lal, 2009). Low crop yields in traditional agriculture are caused by several issues, including soil degradation, restricted access to modern agricultural methods, and the consequences of climate change (Spielman and Pandya-Lorch, 2009; Lambin and Meyfroidt, 2011). Farmers may enhance their livelihoods, boost crop yields, and add to the general resilience of agricultural systems by comprehending and addressing these factors (Basarir et al., 2022).

Vertical farming enhances crop yields

With precise control of environmental elements like light, temperature, and humidity, vertical farming may provide ideal growing conditions that accelerate growth, increase yields and year around growth (Ptak et al., 2024) and it effectively enhances the total output per unit of land or space and enhances the available growing area by stacking growing beds or shelves vertically (Oh and Lu, 2023). Vertical farming techniques generate larger yields than typical seasonal farming methods because they allow for continuous cultivation and several harvests throughout the year (Mishra et al., 2024). By making it easier to cultivate a wide range of crops, including ones that aren't often cultivated in some climates, vertical farming can increase crop diversity and possibly yields overall (Qu et al., 2024). Increased crop yields and productivity in vertical farming systems are achieved by the use of cutting-edge technologies like robotics, artificial intelligence, and automated nutrient delivery systems (Zhu and Marcelis, 2023).

Climate change

According to the World Meteorological Organization, the average temperature increase in 2023 is 1.54 degrees Celsius above the pre-industrial period. Climate change increases the frequency and intensity of extreme weather events, such as floods, droughts, and storms, which can disrupt traditional agriculture but can be mitigated in controlled environments of vertical farms (FAO, 2017; Hernández et al., 2018). Changes in precipitation patterns and increased water scarcity due to climate change emphasize the importance of water-efficient farming methods like hydroponics and aeroponics, commonly used in vertical farming (Tilman et al., 2001; Naskali et al., 2022). Vertical farming provides climate-controlled environments that buffer against temperature variability, allowing for consistent crop production despite temperature fluctuations associated with climate change (Sani et al., 2020). Climate change alters pest and disease patterns, threatening crop productivity (Singh et al., 2023). Vertical farming offers resilience to climate change impacts by providing a flexible and adaptive production system. Its modular design allows for rapid adjustments in response to changing environmental conditions (Despommier, 2019). Vertical farming can further boost output and lessen its environmental impact by utilizing automation and technology (Benke and Tomkins, 2017).

Urbanization

According to the book of statistics 2023, the share of urban population was projected to have increased to 56.9 percent in 2022. It is generally higher in the developed (79.7 percent in 2022) than in the developing world (52.3 percent). As urban areas expand, available land for traditional agriculture decreases, necessitating innovative solutions like vertical farming to utilize limited space efficiently (Wang and Kintrea, 2021). Urbanization brings populations closer to markets, enhancing the viability of urban farming methods like vertical farming that can supply fresh produce directly to urban consumers (Specht et al., 2014). Urbanization fosters a growing interest in locally sourced food due to environmental concerns and the desire for fresher produce, driving the adoption of urban farming methods like vertical

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farming (Sanyé-Mengual et al., 2015). Moreover, the proximity of vertical farms to urban populations reduces transportation costs and emissions associated with food distribution (Specht et al., 2014). Additionally, vertical farming can repurpose underutilized urban spaces such as abandoned buildings or rooftops, contributing to urban revitalization efforts (Singh et al., 2023). There are multiple advantages to vertical urban farming, such as better food security, less of an influence on the environment, and the possibility of creating multipurpose urban areas (Al-Kodmany, 2018b; Khalil and Wahhab, 2020; Zaręba et al., 2021). In addition to lowering food miles and related greenhouse gas emissions, it can aid in addressing the problems of scarce green space, population expansion, and agricultural shortages (Al-Kodmany, 2018a). A 50% decrease in urban density would result in households needing to buy an extra 100 gallons of petrol each year, according to the National Highway Traffic Survey (NHTS).

Health

Traditional farming methods often lead to the destruction of both natural and human environments due to insufficient attention to environmental concerns (Despommier, 2010, 2013; Touliatos et al., 2016). This neglect results in soil erosion and pollution, resulting in notable water runoff. A WHO evaluation states that over half of farms worldwide continue to utilize raw animal manure as organic debris, which can attract flies and spread plant diseases and weed seeds that might be harmful to people who eat the food (Al-Kodmany, 2018a). Additionally, pesticide and herbicide use in traditional agriculture can contaminate agricultural runoff, but this risk can be mitigated through controlled indoor farming environments (Cho, 2011). Cho (2011) states that pest invasion and crop damage are also lessened in closed environments.

The ecosystem

Human agriculture, particularly its advancement and intensification, has had a profound impact on natural ecosystems, leading to habitat destruction, eutrophication, and a decline in biodiversity (Matson et al., 1997; Tilman et al., 2001; Emmerson et al., 2016) As stated by Dickson Despommier, "Farming has impacted the Earth's ecosystems more than any other activity" (Corvalan et al., 2005). This has been primarily driven by the conversion of grasslands and woodlands into agricultural land to address the increasing needs of a burgeoning worldwide population (Walker, 1999). Over the past 50 years, about 1,812,992 km^2 of hardwood forest in the Brazilian rainforest have been cleared for farmland (Corvalan et al., 2005). One potential solution to mitigate the negative impacts of climate change and restore biodiversity is the adoption of indoor vertical farming (Benke and Tomkins, 2017; Despommier, 2019; Maheshwari, 2021; Zaręba et al., 2021). Moreover, it is seen as a robust strategy for combating climate change, tackling issues including waste management, carbon emissions, and the consequences of urban heat islands (Maheshwari, 2021). The vertical farming approach is thought to be a workable way to boost urban food sufficiency, and it may also help to reduce resource use and restore forests (Despommier, 2019).

Vertical farming: unpacking the growing trend

Vertical farming is growing more and more prominent because it promotes efficient utilization of available space in urban places where there is a shortage of land. The restricted amount of land available in cities may be addressed by vertical farming, which makes effective use of available space. By harnessing vertical space in skyscrapers or other structures, vertical farming maximizes the use of available land and enables multiple layers of cultivation (Chatterjee et al., 2020). Vertical farming is also attractive because it offers better control over growing conditions. By employing controlled environments, vertical farms can optimize features such as humidity, lighting, and temperature to create ideal growing conditions (Maurya P. et al., 2023). This leads to enhanced crop yields and better-quality produce. Additionally, vertical farming reduces the need for extensive transportation of food from rural areas to urban centers (Van Delden et al., 2021). This avoids the carbon emissions associated with long transportation distances and reduces dependence on traditional agricultural systems (Maheshwari, 2021). Overall, people are choosing vertical farming because it allows for efficient use of space in urban centers, increases crop yields, provides better control over growing conditions, diminishes the demand for transportation, and promotes sustainability in food production. Vertical farming is becoming a popular choice for various reasons (Avgoustaki and Xydis, 2020).

Methods of vertical farming

Vertical farms employ one of three soilless techniques like hydroponics, aeroponics, and aquaponics to supply nutrients to the plants. This is a synopsis of the three systems:

Hydroponics

Hydroponics, the dominant cultivation method employed in vertical farming, entails growing plants in nutrient-enriched liquids without the use of soil (Maurya P. K. et al., 2023). Plant roots are immersed in a nutrient solution that is consistently monitored and circulated to uphold the appropriate chemical balance (Ahmed et al., 2021). This technique guarantees ideal growth and development by enabling fine control over the nutrients given to the plants (Sathyanarayan et al., 2023).

Aeroponics

NASA developed this revolutionary indoor growing process. NASA coined the word "aeroponics" in the 1990s to describe the efficient growth of plants in space without soil or much water. While still considered unconventional, aeroponic systems are increasingly prevalent in vertical farming (Alneyadi et al., 2024). These systems, which utilize significantly less water up to 90% less than hydroponic systems. Chittibomma et al. (2023) deemed the most efficient method for cultivating plants in vertical farms. These methods have been employed in an array of contexts, including seasonal plant cultivation, commercial production, and research (Wheeler, 2022). Studies on plant-microbe interactions and plant root development have also made extensive use of aeroponic systems, which offer a flexible and practical platform for investigation (Cai et al., 2023).

Aquaponics

Aquaponic systems integrate fish and plants within a unified environment, expanding upon the principles of hydroponics. In this setup, fish raised in indoor ponds generate nutrient-rich excrement, which is utilized to nourish plants within vertical farms. These plants, in turn, clarify the effluents, which is subsequently recycled back into the fishpond (Ramchiary et al., 2022; Vargas et al., 2022; Okomoda et al., 2023). While aquaponics finds application in lesser-scale vertical farming setups, commercial vertical farms typically focus on the cultivation of a limited range of fast-growing vegetable crops, omitting the aquaponic component. This streamlined approach simplifies both economics and production processes while optimizing efficiency (Birkby, 2016) (see Table 2).

High-tech vertical farming methods

Research on vertical and urban farming seeks to improve the long-term reliability of the food we consume by applying cutting-edge strategies that provide higher yields with less water usage than conventional agricultural practices (Kalantari et al., 2017). The agricultural sector is changing thanks to cutting-edge farming technology including closed plant production systems with artificial light (Kozai, 2012), smart aeroponic systems for IoT vertical agriculture (Belista et al., 2018), and LED lighting in vertical farming systems (Nájera et al., 2022). Herbicides and insecticides are no longer necessary thanks to these systems, which provide each plant with the precise nutrients and amount of light it needs. Additionally, as evidenced by the higher nutritional components and production in horticultural crops, they optimize the value of food and nutrition. In vertical aeroponic farming methods, the adoption of LED illumination has proven very effective in increasing photosynthetic capabilities and crop output (He, 2015). These innovations can greatly increase food security and sustainability. Furthermore, vertical farming offers the possibility of customizing product flavors to meet consumer preferences. These cutting-edge farming techniques mark a revolutionary change in the production of food and farming, and since they can flourish in little space, they are especially well-suited for urban settings as stated by Healy and Rosenberg (2013). Vertical farming minimizes water usage by utilizing innovative irrigation systems such as aeroponics or hydroponics, where plants are grown in a nutrient solution instead of soil. These systems can significantly reduce water consumption compared to traditional farming methods, making it a more sustainable option (Klassen et al., 2020).

The rise of vertical farming in vegetable production

The IPCC's 2007 report prompted a shift toward exploring alternative methods of food production, such as permaculture, hydroponics, aeroponics, and aquaculture, in response to the escalating challenges posed by climate-induced crop failures. Futuristic ideas proposed by pioneers like Buckminster Fuller and

TABLE 2 Advanced farming techniques with significant advantages and useful technology.

Farming techniques	Important traits	significant advantages	Common/Useful Technology	References
Hydroponics	Utilizing water as a medium for crop production without traditional soil	It minimizes the need for fertilizers and pesticides by successfully mitigating soil-related cultivation issues.	Advanced technology is a key component in modern agriculture. This technology includes computerized monitoring systems, laptops, tablets, and smartphones, which are used in conjunction with various applications for food cultivation. Additionally, remote management systems, automatic stacking mechanisms, and high-tech LED lighting that can be customized are employed to improve efficiency. Renewable energy sources, such as wind, solar and geothermal power, are integrated into the farming process, along with anaerobic digesters and closed-loop systems for sustainability. The use of robotics, pesticides, rainwater collection devices, water circulation and recycling, and climate control via AC/HVAC systems, including the application of nutrient management strategies are all necessary components of modern agriculture.	Sathyanarayan et al. (2023) Sharma et al. (2018); Maurya P. K. et al. (2023) Nájera et al. (2022) Ullah et al. (2023)
Aeroponics	A replication of hydroponics where plant roots are misted with nutrient solutions.	Aeroponics consumes a lower amount of water compared to alternative plant cultivation techniques.		Chittibomma et al. (2023) Wheeler (2022) Cai et al. (2023) Nájera et al. (2022) Ullah et al. (2023)
Aquaponics	Aquaponics and hydroponics have been integrated within this system.	The cultivation system establishes symbiotic connections between plants and fish through the utilization of fish tank waste to nourish hydroponic production beds. Additionally, the hydroponic bed conserves water for the fish pond, resulting in a mutually advantageous arrangement.		Ramchiary et al. (2022); Vargas et al. (2022); Okomoda et al. (2023) Zaręba et al. (2021) Ullah et al. (2023)

TABLE 3 Modern vertical farming system's perks.

S. no.	Parameters	Remark	References
1.	Areas designated for cultivation	Vertical farms offer approximately ten times more growing space compared to traditional farms.	Despommier (2010)
2.	Variety of crops suitable for cultivation	A vast range of crops may be grown on vertical farms. Crop selection may be flexible in vertical farms due to controlled environment, market demand, climate, and available space.	Zhu and Marcelis (2023)
3.	Crop yield	Traditional open field agriculture and other farming techniques cannot achieve the same frequency of crop rotations per year as vertical farms, irrespective of external conditions. Due to enhanced environmental control, crops can be harvested at a faster rate.	Maurya P. et al. (2023)
4.	Harvests	Regardless of external circumstances, controlled interior temperatures offer consistent and predictable growth cycles, enabling growers to fulfil the demand of consumers.	Rivero and Salvi (2023) Aung and Chang (2014) Kawasaki and Yoneda (2019)
5.	Combining multiple technologies	Automated monitoring and control systems would ensure the vertical farm's total security and safety.	Wang et al. (2021) Saad et al. (2021)
6.	Water quality and consumption	All of the fresh water in the vertical farm is completely filtered. Comparing vertical farming to conventional open-field farming methods, water use is typically 10% lower.	De Kreij et al. (2003)
7.	Energy consumption	High-efficiency LED lighting technology allows for maximum plant growth with lowest energy use. Controlling photosynthetic wavelengths using a computer in rhythm with the growing phase of crops is necessary to maximize harvests while consuming less energy.	Yeh and Chung (2009) Olle and Viršile (2013)
8.	Quality of air	The temperature, CO2 levels, and humidity of air in the vertical farm would consistently be upheld at optimal levels.	Al-Kodmany (2018b), Despommier (2013), Maurya P. et al. (2023)
9.	Mineral and Nutrient quality	A vertical farming system employs bioactive nutrients, which provide organic minerals and enzymes to promote plant development throughout the crop cycle.	De Kreij et al. (2003)
10.	Characteristic of the light	For the best growth rates, highly effective high pace low-energy LED lighting needs to be developed and employed.	Massa et al. (2008) Yeh and Chung (2009)

John Todd in the 1930s and 1960s, respectively, gained practical relevance as traditional outdoor farming faced serious threats by the year 2000. By 2008, countries like Japan, Korea, Singapore, and Sweden started supporting demonstration programs, including the construction of Vertical Farms (VF), signaling a paradigm shift in food supply management.

Vertical farming has gained traction as a solution to the challenges posed by traditional agriculture, such as limited land availability and dependence on weather conditions. By utilizing vertically inclined surfaces, such as skyscrapers or indoor structures, vertical farming maximizes the use of space and resources. This means that vertical farming can cover a significant area for vegetable cultivation in urban settings, where land is scarce (Despommier, 2010). Nowadays vertical farming has been working as the skyscraper gardens or skyline farms in many cities. Vertical farming plays a crucial role in shaping the urban landscape and contributing to sustainable urban agriculture (Zaręba et al., 2021). With its innovative design and proper management, vertical farming can transform unused spaces into productive vegetable gardens. Moreover, vertical farming is considered a symbol of societal well-being and urban sustainable development. Vertical farming can cover a significant area for vegetable cultivation in urban settings, particularly in areas where land is limited (Khalil and Wahhab, 2020; Zhou et al., 2022). This allows for the adaptation of vertical farming to different available spaces in urban areas, making it a versatile and scalable solution for vegetable cultivation (Khalil and Wahhab, 2020). Overall, the area covered under vertical farming on vegetables can vary greatly depending on the specific design, patterns, and sizes of the vertical farm (Zhu and Marcelis, 2023) (see Table 3).

Technological trends in vertical farming

Sensing technology and actuators

For effective environmental management and to maximize plant development, sensors are essential in vertical farming (Chuah et al., 2019; Ullah et al., 2023). These sensors can be integrated into a range of systems, including electronic systems (CPS) (Chuah et al., 2019) mobile sensor networks and Internet of Things (IoT) founded applications (Abbasi et al., 2014). These sensors monitor variables like humidity, temperature, intensity of light, CO2 levels, level of nutrients, and pH. They offer real-time analytics and data, enabling remote monitoring and control as well as data-driven for decision-making (Chuah et al., 2019; Wang et al., 2021; Ullah et al., 2023). Furthermore, by tracking soil conditions and supplying crucial information for maximizing crop development, soil-based sensors and plant monitors can further improve precision agriculture (Yin et al., 2021).

In advanced vertical farming, the integration of sensors and actuators is vital for automation, efficiency, and simplified management (Singh and Singh, 2020). Actuators interact with environmental aspects and gather crucial data on temperature, pH alterations, light, decreasing the need for ongoing human intervention (Saad et al., 2021). Actuators respond to this data by regulating equipment associated with characteristics such as ventilation, cooling, refrigeration, humidity, illumination, pressurization, ensuring optimal agricultural conditions without heavy human involvement (Sivamani et al., 2013).

Temperature sensors utilizing thermostats or resistance temperature sensors provide real-time temperature measurements converted into electrical signals, while maintaining appropriate humidity levels is also key for plant development. Precise moisture conditions and exact temperature control are crucial for optimal plant development as various plant species necessitate different temperature ranges for photosynthesis (Lakhiar et al., 2018). Accurate measurement of CO2 levels is essential in vertical farming, with devices like chemical carbon dioxide sensors (CCDSs) and nondispersive infrared carbon dioxide sensors (NICDSs) aiding in monitoring and controlling CO2 concentrations, directly impacting plant growth and development and productivity of farm (Dhanaraju et al., 2022).

Texture sensor

It is employed to measure surface of soil, soil depth, soil density. Few research described many types of technical devices available to test soil electrical conductivity and texture (Martínez et al., 2021). These soil texture sensors also offer indirect data on soil health and electrical conductivity (Saad et al., 2021).

Organic matter sensing device

The component of soil known as organic matter is made up of substances produced by soil species, cells and tissues of soil microbes, and leftovers from plants and animals at various stages of decomposition (Ravansari et al., 2021). The physical and chemical characteristics in soil, in addition to the soil's ability to supply balancing ecosystem services, may all be monitored with the use of soil organic matter sensors. For the consistency and functionality of soil, in particular, the presence of these sensors is thought to be crucial. Soil organic matter sensors monitor several aspects of soil function, such as nutrient cycling with storage, buffering capacity, water retention, fertility, pollutant adsorption and retention, changes in the composition of the soil, accumulation, and fertility (Frazão et al., 2019). Urban VF crops are produced using these sensors to choose sustainable soil (Saad et al., 2021).

Plants to develop healthily in indoor vertical farms, 8 to 10 h of artificial light are needed each day, the amount of light needed varies depending on the type of plant (Despommier, 2010; Kato et al., 2010). Light intensity sensors such as photodiodes, phototransistors and photoresistors, guarantee plants to assure the appropriate light amount, considering different plant varieties' light requirements. These sensors ensures current information on intensity of light and particular wavelengths, ensuring optimal light conditions for vegetation development (Saad et al., 2021). Water-level sensors automate the monitoring of nutrient-solution reservoirs, contributing to accurate monitoring and control. Electrical conductivity (EC) and pH sensors are also utilized to measure nutrient solution parameters, augmenting nutritional balance and stability for improved nutrient absorption (Resh, 2022). Integrating sensors for light intensity, water level, temperature and EC/pH allows growers to obtain real-time insights, aiding in informed decision-making and enhancing crop quality and quantity in vertical farming settings (Yin et al., 2021).

Actuators serve as vital components in vertical farming, offering precise control over environmental conditions. These mechanisms transform electronic impulses into mechanical movements, enabling dynamic adjustments that foster plant growth. Actuators are indispensable in regulating airflow, modifying lighting positions, and managing irrigation systems for enhanced plant development outcomes (Sivamani et al., 2013; Saad et al., 2021). Actuators maintain constant temperature and air quality through ventilation system regulation, which is vital for the healthy development of plants. Actuators also control irrigation procedures by regulating pumps and valves to precisely supply the right quantity of water to the vegetation, reducing waste and guaranteeing steady hydration, and improving the effectiveness of water management (Despommier, 2010) (see Figure 1).

Nutrient-sensitive systems

Maintaining adequate nutrient levels in hydroponic setups is crucial because plants require varying quantities of nutrition during various growth phases for physical development and physiological maturity (Trejo-Téllez and Gómez-Merino, 2012). While, an excessive influx of stock solution into the nutrient mixing tank might trigger to toxicity in the intended nutrient solution, while insufficient flow might lead to a nutritional shortage. Both scenarios can hinder plants' long-term growth and maturation (Bamsey et al., 2012). Traditionally, farmers have depended on visual cues in plants to identify nutrient deficiencies or toxicity, which are only visible after extended periods of inadequate nutrition (Horst et al., 2006). Furthermore, identical visual symptoms resulting from various nutrients shortages sometimes result in incorrect diagnoses and ineffective nutrient treatments (Marschner, 2011). A common method for monitoring nutrient levels in hydroponic solutions is to constantly measure pH levels and electrical conductivity. While this approach provides rapid information on nutrient levels, it falls short in pinpointing specific nutrient ions in the solution (see Figure 2).

Plant observation and governing systems

Monitoring and governing plant conditions is crucial for maximizing crop quality in vertical farming methods. In recent times, IoT technology has received significant acknowledgment and has been extensively employed in modern agriculture, especially vertical farming production and management (Marković et al., 2015; Dhanaraju et al., 2022). The crop-growing environment is continually monitored and controlled by IoT-enabled sensors and actuators, enabling real-time monitoring of critical parameters including humidity, temperature, soil moisture, water pH and controls the crop-growing environment, improving food output while consuming less resources (Aiswarya et al., 2023). The incorporation of IoT-based applications has garnered considerable attention due to its capacity to enhance monitoring and precise control, thereby enhancing agricultural sustainability. These interconnected systems utilize a

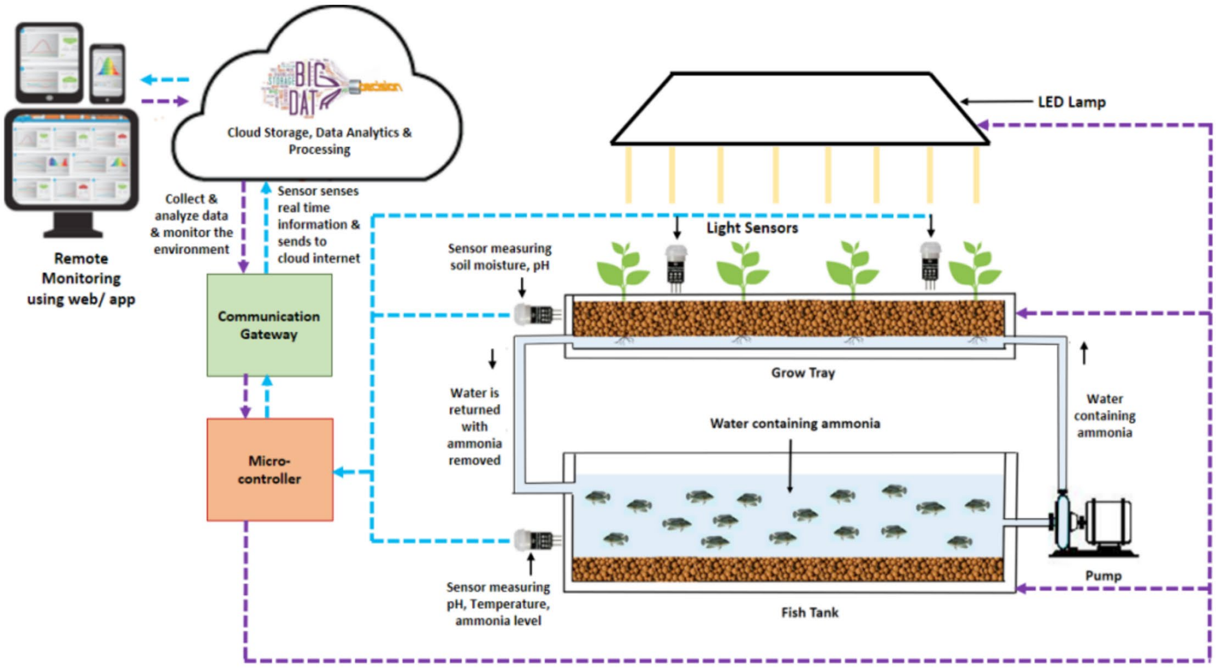

FIGURE 1
Schematic representation of implementation of IoT in vertical farming.

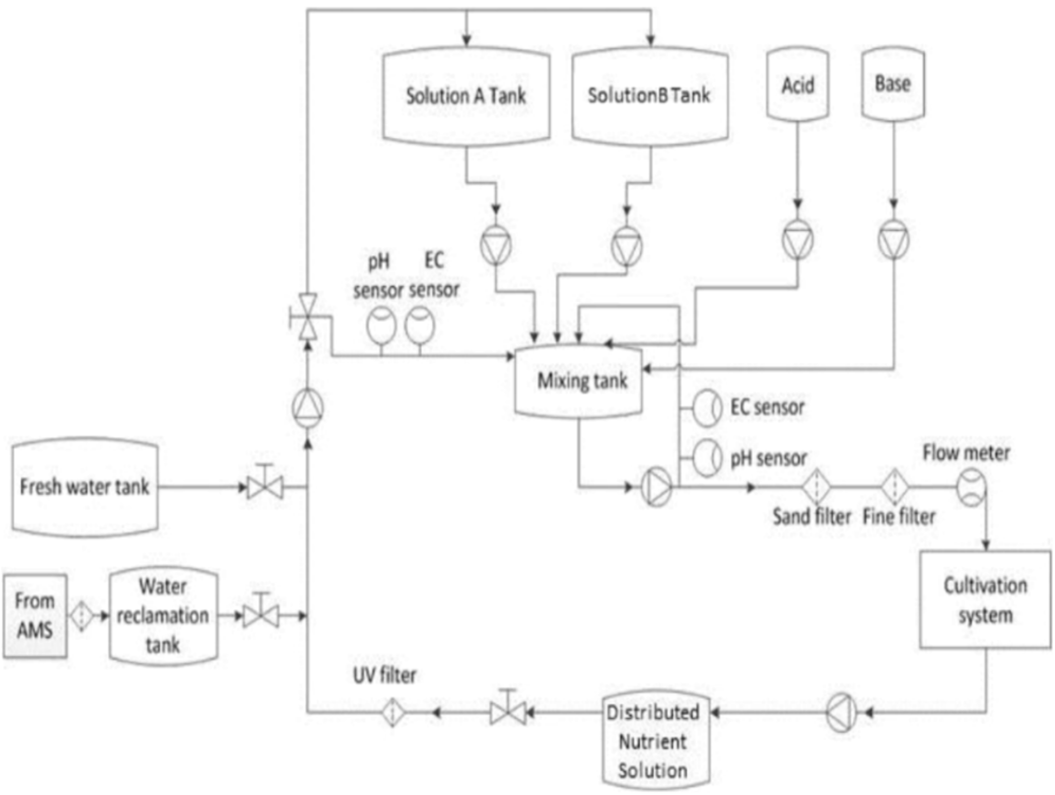

FIGURE 2
Schematic representation of nutrient delivery system for a module.

variety of sensors, actuators, and data-analysis tools to offer real-time monitoring of essential environmental parameters (Morella et al., 2023). The advanced applications of the platform furnish farmers with insights into crop-growing circumstances, empowering them to execute prompt action and form decisions that contribute to ensuring crop quality and yield.

Growers can customize habitats for various crops using IoT-enabled devices, verifying regular growth parameters for specific plants from a distance (Quy et al., 2022). This lessens resource wastage, decreases reliance on pesticides, and minimizes the environmental effect in contrast to conventional farming methods. Sensors providing data on water and nutrient levels are utilized to tackle challenges related to the efficient management of water and nutrients. When crop demand is high, this knowledge directs the exact utilization of these resources. Moreover, real-time meteorological data may be readily integrated into IoT platforms, improving their capacity to forecast atmospheric conditions and allowing for proactive modifications (Kabir et al., 2023). The Internet of Things plays a crucial role in managing diseases and pests by using data analysis and contemporary technologies. As IoT devices are user-friendly in the agricultural domain, scientists are encouraged to combine Internet of Things solutions with machine learning techniques (Mehra et al., 2018; Rezk et al., 2021). By using sensors with picture recognition built-in, it is possible to quickly identify symptoms of illness or infestation. The potential for revolutionizing urban agriculture through the incorporation of IoT technologies in vertical farming is significant (Saad et al., 2021).

Visual sensors record visual information, which offers important insights into the growth and health of plants. Plants, foliage, and fruits are continually observed by high-resolution cameras, which provide real-time data on growth trends, disease signs, and stress indicators (Schima et al., 2016). Using computer-vision algorithms to evaluate plant density, size, and even fruit ripeness, visual sensors automate plant monitoring and improve operational efficiency by streamlining labour-intensive tasks. These data also help detect problems early and enable timely interventions (Paulus et al., 2014). By using visual sensor technology, vertical farmers may maximize resources, make educated judgments, and modify their planting operations. This data-driven strategy increases yields, promotes sustainable agricultural methods, and guarantees healthy crop growth (Paul et al., 2022).

Unmanned vertical farming systems

By fusing creativity and technology, automated vertical farming methods offer a cutting-edge agricultural inventions that will transform crop cultivation (Wang et al., 2021). These systems optimize plant development by combining automation, robotics, and cutting-edge sensing technologies to produce controlled circumstances in stacked layers. These systems provide precision management of environmental factors including temperature, light, humidity, and fertilizer supply, assuring ideal circumstances for plant development. They do this by combining real-time data with precise control mechanisms. This precision leads to increased crop yields and a more effective utilization of resources, which significantly lowers labour costs (Saad et al., 2021). Real-time monitoring and automated nutrient and water delivery systems enable more efficient use of resources, which preserves a lot of water and lessens reliance on outside nutrient sources (Avgoustaki et al., 2022). Automated vertical farming systems can produce crops year-round since they are not affected by seasonal or weather fluctuations, which adds to the security of food supply (Saad et al., 2021). The merging of sensors and data analytics enables immediate understanding of plant health and growth status, which also provides a platform for testing out novel crop varieties, cultivation techniques, and technology (Wang et al., 2021). To increase productivity, cut labour expenses, and improve overall efficiency, automated control systems are being included into a vast array of agricultural techniques, aquaculture, animal farming, and controlled greenhouses (Siskandar et al., 2022).

Automated vertical farming systems

Vertical farming automation provides a solution to problems including high labour costs, talent shortages, and increased productivity requirements. In vertical farming methods, fewer human interactions lower the risk of illness while also enhancing production and safety (Kozai, 2012; Van Delden et al., 2021). The ultimate triumph of vertical farming hinges on various automated processes, such as automated harvesting, bed maintenance and reloading, automated irrigation, lighting, fertilization, and crop surveillance through visual systems (Michael et al., 2021). These technologies permit IoT-connected farming for accurate surveillance and feedback on growth circumstances, reduce expenses, and provide critical data for optimal solutions (Bhowmick et al., 2019). The relevance of automation is shown by the emergence of tiny vertical farm systems intended for use in homes or small businesses. However, total automation and potential production optimization are now not attainable because of necessity on manual planting and harvesting (Hegedűs et al., 2023). On the other hand, entirely automated vertical farming systems demonstrate the potential of advanced software-driven setups by including a variety of functions like as lighting regulation, nutrient supplementation, harvesting, cleaning, and sowing. In vertical farming, white light-emitting diode (LED) lighting is an effective light source for commercial plant growth. A study was carried out to find out how white LED light sources affected the development and quality of butterhead and romaine lettuce. The highest light and energy consumption efficiencies were also observed. These findings support the use of certain white LED light sources in vertical farming and demonstrate the beneficial impacts of such light on lettuce growth and quality (Nguyen et al., 2021). An effective robot system for collecting cucumbers using a human-centered approach. In particular, to provide steady and effective harvesting, harvest ordering, visual servoing, and end-effector-based manipulation features were combined. The trials' findings demonstrated that harvest ordering improved battery efficiency while reducing trip distance and harvesting time (Park et al., 2023). These systems exceed human capabilities by 10–30 times, enabling real-time monitoring, accurate planting, and swift seeding on a 20-layer vertical farm. The cost factor is still an issue, though, as this entirely autonomous system is two or three times costlier than the popular semiautomatic method (Kozai, 2012; Maurya P. K. et al., 2023).

Robotic vertical farming systems

Robotic technology is being used more and more in vertical farming due to the financial and physical limitations of using human labour (Shamshiri et al., 2018). Nevertheless, there are obstacles in the way of creating efficient robotic systems, such as the requirement for cooperation between humans and robots and the capacity to function in unstructured agricultural settings (Bechar and Vigneault, 2016). Because of the physical constraints of large structures and the great density of farmland, human labour is both impractical and wasteful. Complex tasks like precise harvesting, upholding environmental regulations, decreasing human error, and guaranteeing the consistency necessary for the highest possible crop yields and quality are all tasks that robotic systems excel at (Fountas et al., 2020). Robotic vertical farming systems decrease reliance on human labour by effectively and precisely managing various challenges. Labour expenses make up a considerable portion of overall spending (between 25 and 30 percent), robots prove to be accurate, reliable, and efficient workers in a diverse range of jobs, hence reducing both fixed and operating costs. Robotics and automation are enhanced by the use of smart technology, which raises production and efficiency (Starostin et al., 2023). In vertical farms, autonomous robotic platforms with flexible sensors can play a crucial role in achieving these objectives (Avgoustaki et al., 2022). iFarm is a customizable indoor vertical farming system that employs effective power management, LED lighting, and automatic climate control to enable year-round, pesticide-free plant growth. Among its cutting-edge technologies are a neural network that computes plant mass dynamics and a chatbot for analyzing plant images (Kabir et al., 2023). Low-altitude multispectral pictures may be used to identify plant growth and quality, which can reduce the amount of water and nutrients that plants consume (Avgoustaki et al., 2022). This non-intrusive vision method is perfect for self-governing robots in vertical farms. A robot for harvesting and planting on the City Crop automatic indoor farm was proposed by Marchant and Tosunoglu (2017).

Vertical farming with drones

A new era of agricultural innovation is brought about by the combination of drone technology with vertical farming, which reinvents crop growing in controlled environments. Drones and vertical farming together have the ability to transform agriculture, bringing sustainable food production and solving global issues (Tsouros et al., 2019). The confluence of these two innovative technologies holds immense promise to change agricultural practices and help address global challenges including the security of food, limited resources, and environmental sustainability. Drones provide accurate aerial photography and data-driven insights; they are complemented by the climate-controlled, space-efficient environments of vertical farming (Daponte et al., 2019). A revolutionary autonomous drone made exclusively for horticulture, such as flower recognition and seed germination, has been unveiled by Corvus Drones (Kabir et al., 2023). Additionally, they aid in conserving wild bee populations, which are diminishing due to factors like climate change, urban development, and pesticide usage, ultimately benefiting plants reliant on outdoor pollinators (Glick, 2023). Nokia Bell Labs and Aero Farms have collaborated since 2020 to investigate and improve ideas, including trials with commercial crops. Nokia Bell Labs is an expert in sensor data pipelines, AI for mobile sensors, improved photography, private wireless networks, and autonomous drone control (Kabir et al., 2023). Drones that operate on their own take pictures of vertical farm crops while collecting information on plant health markers including dimensions of leaf, stem height, coloration, bending, speckling, and damage (Ghazali et al., 2022). Drones with cutting-edge sensors and artificial intelligence (AI) can maximize resource utilization and deliver data on plant development and health in real-time (Kim et al., 2019). iFarm is effectively testing computer vision technology to use unmanned aerial vehicles (UAVs) (Nunes, 2023), to oversee the developmental phases of plants in vertical farming setups. Their work focuses on techniques for calculating plant weight from pictures and choosing the optimal lighting modes depending on energy usage and leaf growth rate (Bhushan and Negi, 2023). Additionally, they are looking at the use of drones that are unmanned to speed up data collection and enhance neural network performance (Lawrence et al., 2023). According to Puri et al. (2017), this method can greatly lower expenses while raising yields. The absence of a standardized UAV workflow in agriculture, however, continues to be a problem (Tsouros et al., 2019). Agricultural unmanned aerial vehicles (UAVs) appear to have a bright future despite this, as they continue to expand and improve (Kim et al., 2019).

Media selection

A substance that promotes plant development is called a growth medium. Numerous non-toxic porous materials, such as expanded clay, rock wool, pumice, perlite, volcanic minerals, and dust from coconut coir, are used as substrates for plant development (Gruda and Bragg, 2021). These media's capacity to hold moisture and offer a steady environment for plant roots makes them very well-liked in vertical farming. However, the environmental problems raised by the usage of rock wool and peat in these mediums have prompted a quest for more sustainable replacements (Barrett et al., 2016; Gruda and Bragg, 2021). Using sustainable, reasonably priced, and renewable materials that satisfy environmental and quality standards is the way of the future for growth medium (Gruda, 2019; Sabatino, 2020). The choice of media used in vertical farming can vary based on the particular system and crops being grown (Kalantari et al., 2017). These non-soil mediums are commonly used in vertical farming due to their ability to retain moisture and provide a stable environment for plant roots. Some common types of media exploited in vertical farming include

Peat

The most popular medium for growing plants is peat. Peat generally tend to possess excellent chemical, physical and biological properties for plant growth (Krucker et al., 2010). These characteristics might differ greatly depending on the circumstances surrounding the production of the peat (Bragg, 1990; Michel, 2010). For example, when compared to older and more decomposed deposits, younger and less decomposed peats often have a better water-holding capacity (Schmilewski, 2008). Manufacturers of plant-growing media are moving toward a future with less peat owing to rising consumer knowledge of environmental issues, legislative pressure to restrict the mining of ecologically valuable peatlands, and an awareness of personal accountability (Gruda, 2019). In horticulture, a variety of organic compounds have been offered as a peat substitute for plant growth media (Barrett et al., 2016). As plant-growing media, only composted bark, wood fibre, green waste compost and coir pith have proven to be trustworthy.

Biostrate

It is a recently created microgreen growth medium that is extensively accessible on the market. It is a bio-based fabric called Biostrate that was created especially for hydroponic microgreens and baby salad greens it is utilized in soilless and hydroponic systems, is composed of biodegradable materials like wood Fibers and offers the perfect conditions for plant roots (Reddy and Yang, 2005). Because of its lightweight design and efficient moisture and nutrient retention, it is especially well-suited for hydroponic applications, including microgreen production (Du Jardin, 2015). Applying plant biostimulants can further increase the utilization of Biostrate by enhancing crop quality and nutrient absorption (Halpern et al., 2015). BioStrate is user-friendly and lightweight and ability to decompose naturally (Pandey et al., 2005). Therefore, Biostrate will be studied as a microgreen generation medium and its potential to provide a higher yield compared to other biodegradable environmentally friendly media.

Rockwool

Rockwool is originated by melting chalk and basalt rock together at very high temperatures. This method yields a substrate with a thick structure made up of long fiber strands that resemble steel wool in texture and appearance. According to Borošić et al. (2010), rock wool can be mulched over the soil, blended into the soil, or utilized as a chopped substrate component. Rockwool is a commonly used media in vertical farming due to its versatile properties. It provides excellent water retention capabilities, allowing for efficient nutrient uptake by plants. Additionally, rock wool offers good air circulation around the roots and provides stability and assistance for the plants during vertical growth (Gruda, 2019).

Coco coir: a sustainable growing medium

Natural fibre called coir is derived from the husks of coconuts and has a variety of uses (Stelte et al., 2023). Its physical characteristics, such its capacity to retain water and aeration, make it especially well-suited for various uses (Wang and Huang, 2009). Widely used growing media in vertical farming (Reddy and Reddy, 2019). Before being used as a growth medium, coir needs to be washed many times in fresh water and undergo a "buffering" procedure, which involves adding calcium nitrate to the material to replace dangerously high amounts of salt and potassium (Poulter, 2011; Gruda, 2019). It is biodegradable, renewable, and environmentally friendly. Coir is often used in vertical farming for growing a variety of crops, including vegetables, herbs, and ornamental plants. It can be utilized unprocessed or transformed into a variety of forms such as coir pellets, coir mats, or coir bricks for different growing applications (Reddy and Reddy, 2019).

Expanded clay pellets

Expanded clay pellets are lightweight and porous, providing excellent aeration and drainage for plant roots in vertical farming methods (Zhu and Marcelis, 2023). These pellets, which are made of clay, rice husk ash, and phosphate rock give plant roots superior drainage and aeration. Expanded clay pellets are often used in vertical farming due to their ability to promote efficient root development and nutrient absorption (Tala et al., 2020).

Perlite

Perlite is formed when volcanic rock undergoes further expansion after being superheated. It is light in weight, porous particles that have good aeration and drainage qualities (Varuzhanyan et al., 2006). Its applications extend to enhancing soil drainage and decreasing density when added to potting mixes. Plants may avoid waterlogging and root rot by using perlite, which holds onto some moisture while letting extra water to drain away quickly (Hasan and Dede, 2018). It is sterile, pH-neutral, and does not decompose, making it a durable and reusable growing medium. Perlite is often utilized in vertical farming systems, especially for growing plants that require good drainage and aeration, such as herbs, leafy greens, and strawberries.

Vermiculite

It belongs to the smectite mineral group, it contains significant quantities of potassium and magnesium. Despite being less durable compared to mediums like sand and perlite (Mir et al., 2022). Vermiculite is a very adaptable growth medium that provides several advantages to plants. Its superior water-retention qualities contribute to the roots' continuous hydration. Vermiculite is also neutral in pH, lightweight, and offers adequate root aeration, making it a wonderful choice for a range of plant species (Papadopoulos et al., 2008). It's crucial to remember that for best effects, vermiculite ought to be used in conjunction with other growth medium like perlite or coconut fibre (Landis et al., 1990).

Wood fibre

The term wood fibre which comes from both main (like fresh pine chips) and waste (like shredded pallets) streams of wood, is not well defined in the literature (Maher et al., 2008). The wood Fibers that are created through intensive secondary processing are the ones that are most frequently utilized in commercial soilless growth medium. Fresh wood chips are often extruded via a tiny opening. These chips are typically made from debarked softwoods like pine (Pinus spp.) or spruce (Picea spp.). Their structure is altered by the high pressure and high temperature environment, producing a secondary product that is more stable, sterile, and uniform (Domeño et al., 2010). To lessen microbial N immobilization and the ensuing instability (Gruda et al., 2000), the material is frequently saturated with nitrogen (Maher et al., 2008). Due to its inclination to get compressed and its capacity to hold inadequate plant-available water, it is rarely employed as a stand-alone growth medium component (Maher et al., 2008; Domeño et al., 2010). Rather, its purpose is to enhance the physical characteristics of other constituent materials, such as by decreasing bulk density, expanding air volume, and enhancing rewetting ability (Landis et al., 1990).

Trends and developments in vertical farming

One potential approach to addressing the problems of scarce land and rising urban food demand is vertical farming. It allows for efficient use of space by growing crops on vertically inclined surfaces such as skyscrapers (Avgoustaki and Xydis, 2020). While vertical farming is still considered a relatively new concept, its potential in vegetable cultivation is vast. Vertical farming enables vegetable growers to optimize space utilization and increase crop yields. The area covered under vertical farming for vegetable cultivation varies depending on the design, patterns, and sizes of the vertical farm (Zhu and Marcelis, 2023). Furthermore, vertical farming provides opportunities for sustainable agriculture by diminishing the necessity for transportation and preserving natural resources such as water and energy. This is backed by the development of affordable vertical farming models, particularly beneficial in remote areas experiencing challenging weather conditions (Carrasco et al., 2022). Some sources have suggested that vertical farming can range from small structures to large skyscrapers, offering a wide array of possibilities for vegetable cultivation in urban areas while minimizing environmental impact (Kalantari et al., 2017). Overall, the area covered under vertical farming on vegetables can encompass a broad array of structures and scales, from small-scale vertical gardens to multi-storied vertical farms. For example, smaller-scale vertical gardens may cover a relatively small area and be suitable for residential or community use (Kalantari et al., 2017). Conversely, large-scale vertical farms can cover significant areas, such as multi-storied buildings or even entire skyscrapers (Zhu and Marcelis, 2023). These larger vertical farms can maximize space utilization and greatly increase crop yields, providing a sustainable and effective solution for urban vegetable cultivation (Maurya P. et al., 2023). By putting cutting-edge technology like machine learning, artificial intelligence, and the Internet of Things into practice, VF's quality and efficiency would increase (Swain, 2022).

Conclusion

Vertical farming is aimed to significantly improve food sustainability in urban areas, especially with the projected increase in urban populations. This method offers a range of benefits across social, environmental, and economic aspects compared to traditional rural farming methods. Innovations like hydroponics, aeroponics, and aquaponics are revolutionizing agricultural practices by reducing the reliance on soil-based farming. Vertical farming, which allows for year-round cultivation of crops like maize, potatoes, and vegetables in compact spaces with minimal labour, is particularly advantageous in regions with limited soil and water resources, benefiting marginalized populations. India expects substantial growth in this industry, necessitating the development of cost-effective technologies like low-cost hydroponics. However, ensuring affordability for low-income urban households remains a challenge, exacerbated by issues like slums and food deserts. The rise of vertical farming hinges on various factors including food supply, population size, technological advancements, cultural dietary habits, and access to energy and water resources.

As a technique, vertical farming seeks to improve crop output per unit of land area in order to alleviate the growing strain on agricultural production. It makes use of controlled settings and protected horticultural systems, such as glasshouses, with slope production surfaces or several layers of growth surfaces. Vertical farming has promise, but it's also expensive and complicated. Technical considerations including lighting, growth systems, nutrition for crops, energy efficiency, building, and site selection must be addressed. To improve its technological and financial characteristics, with an emphasis on increasing production and cutting costs, more research is required.

Currently, vertical farming is predominantly directed by the industry, with limited academic research due to funding constraints, leading to a lack of standardization across different enterprises. Data on its feasibility and crop yield often stems from commercial sources or speculation, highlighting the requisite for more scientific investigations. Collaboration between the vertical farming sector and academia is vital to fully realizing its potential and determining its future expansion as a sustainable food production method.

Author contributions

CS: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft. MA: Conceptualization, Data curation, Formal analysis, Software, Supervision, Visualization, Writing – review & editing, Writing – original draft. CI: Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Writing – review and editing. GA: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft. PJ: Resources, Software, Supervision, Validation, Visualization, Writing – original draft.

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