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*Review paper*

# Role of vertical farming for sustainable urban horticulture: A review

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**Abstract: New constraints such as urbanization, food security, farmland scarcity, and escalating greenhouse gas emissions underscore the importance of vertical farming. This eco-friendly method offers a promising solution to traditional farming, aiding a growing global populace in securing sustenance. Resource use efficiency of vertical farming and the ability to produce premium agricultural goods are driving its global appeal. Particularly beneficial in areas with limited soil and water resources, vertical farming could play a vital role in sustaining fruit and vegetable production. Vertical agriculture emphasizes the critical need for urban centers to combat pollution and escalating food expenses by prioritizing self-reliance through local food production. Advanced cultivation techniques like hydroponics and aeroponics make vertical farming viable for urban environments, requiring minimal oversight and yielding higher outputs. Despite its potential, vertical farming encounters obstacles such as steep upfront and operational costs, complexity, and maintenance demands for optimal growth conditions. To promote urban agriculture, there is a need for enhanced extension services to educate and train growers and farmers on vertical farming techniques for producing diverse horticultural yields.**

## 1. Introduction

*What is urban horticulture?*

With each one-degree centigrade increase in temperature, an estimated 10 percent of the current cropping area is predicted to become unusable (Bouteska *et al.*, 2024). This scenario raises concerns about the potential scarcity of land for farming to adequately feed the global population shortly (Clemson University, 2011). Moreover, research indicates that roughly 80 percent of the currently cultivated land worldwide is actively being utilized (Clemson University, 2011). Urban horticulture, involving the precise cultivation of crops for the production, processing, and distribution of food and other goods within urban and peri-urban settings, offers a solution to this challenge. Definitions of

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urban and horticultural practices vary across nations, regions, and local cultural contexts (CDRF, 2010). Horticulture involves creating gardens and growing plants, while agronomy focuses on managing forests, trees, and their products, along with the cultivation of cereals, animal feed, and other agricultural activities (Abegunde, 2014). Horticulture, which encompasses the production of crops for food, medicine, or aesthetics, falls under the umbrella of agriculture. Conversely, agronomy, primarily concerned with field cropping, centers around producing durable goods like fiber, oilseeds, and legumes.

Urban horticulture encompasses the cultivation of edible and medicinal plants such as fruits, vegetables, herbs, and mushrooms in urban areas and their environs, especially in land-constrained settings (Orsini *et al*., 2013). Its applications range from landscaping public spaces to therapeutic uses for individuals with disabilities (Moustier and Danso, 2006). This practice varies in scale and scope, spanning from high-tech intensive methods to small-scale soilless cultivation with localized irrigation systems (Drescher *et al.*, 2006). In developed nations, urban horticulture often occurs on small state-owned, private, or public plots like community gardens, offering not just fresh produce but also social engagement and recreational benefits (Van Leeuwen *et al*., 2017; Nugent, 2000). Conversely, in developing countries, urban horticulture serves as a means to establish self-sustaining enterprises, generating income and fostering social stability (Van Leeuwen *et al*., 2017). Furthermore, urban horticulture enhances access to fresh, nutritious foods through local gardens and plays a significant role in combating obesity and related health issues. By cultivating fruits and vegetables locally, urban communities can increase their intake of nutritious foods. This approach not only offers scarce food resources to migrant communities but also fosters a sense of community and belonging among residents through urban horticulture projects. Community gardens in particular, provide opportunities for social interaction, shared responsibility, and the establishment of support networks, which can contribute to overall well-being and healthier lifestyles. These advancements address malnutrition prevalent in many urban settings (Lovell, 2016). Urban horticulture plays a vital role in stimulating employment opportunities within agriculture, marketing, and processing domains, thereby enhancing livelihoods and boosting supplemental income for all essential participants within the horticultural value network (Orsini *et al*., 2013). Local food production minimizes intermediaries, transportation, storage costs, and handling, thereby reducing the economic and environmental footprint of food production (FAO, 2014). Furthermore, urban horticulture can help alleviate food deserts in underserved communities and provide affordable food options (De Leever, 2010). By offering recreational spaces, preserved environments, and biodiversity, urban horticulture enhances the quality of life for urban residents (Van Leeuwen *et al*., 2017). Pace *et al*. (2018) observed that concerning postharvest storage, lettuces grown in soilless conditions demonstrated superior qualitative and microbiological performance compared to those cultivated in soil. Specifically, the soilless growing system enhanced the storability of lettuces and facilitated the production of uncontaminated raw materials.

### *What is vertical farming?*

Vertical farming, initially implemented by American geologist Gilbert Ellis Bailey in 1915 (Kretschmer and Kollenberg, 2011) and it was revolutionized by Patrick Blanc, who invented and patented a geometric approach that maximizes production efficiency within a compact footprint. This method entails vertically aligning animals and plants for food or other purposes in a soil-free, space-saving design (Anirudh, 2014) that capitalizes on acreage volume, expanding development possibilities in three dimensions compared to traditional farming practices. Vertical farming systems can range from stacked containers to interconnected networks sprawled over multiple acres, adaptable for indoor and outdoor settings. Utilizing biodegradable and reusable mediums, these systems can be powered by alternative energy sources for pumps and sustainably nourished with organic materials. The definition of vertical farming varies based on factors like size, density, control level, layout, structure, location, and objectives, leading to diverse stakeholder perspectives, from viewing it as a minor crop activity to a pivotal component for future food security. The interchangeable use of "vertical farming" as both an activity and a term further complicates its perception (Waldron, 2018).

Essentially, "vertical farming" refers to cultivating plants in multiple layers to maximize yield within a limited surface area. Chin *et al*. (2017) note that vertical gardening serves various purposes, including ecological and financial benefits. For plant enthusiasts, growing plants vertically in confined spaces provides an engaging activity for both plant enthusiasts and experts. For educators, vertical garden cultivation offers a unique and stimulating opportunity for teachers to practically impart science, basic arithmetic, and finance concepts. For Health-Conscious Consumers, vertical planting, based on organic principles, yields cleaner, fresher fruits, and vegetables with minimal chemical input, appealing to those focused on healthy eating. For Business-oriented Individuals, vertical farming provides businesses with a sustainable and efficient approach to food production, creating valuable opportunities for growth and innovation. This controlled setting offers numerous benefits, such as decreased risks of disease and pest outbreaks, reduced environmental impact, and the ability to uphold produce quality while conserving water (Van der Schans *et al*., 2014). Vertical farming systems minimize water usage and streamline food sales and distribution within urban areas, lowering associated costs. Vertical gardening acts as a sustainable substitute for conventional crop cultivation, aiding in the conservation of land for traditional farming methods. Recognized as a cost-effective food production method (Jansen, 2017), vertical farming proves invaluable in land-scarce scenarios, making it an ideal solution for terrace kitchen gardens. Furthermore, vertical farming plays a significant role in promoting organic farming practices (Anirudh, 2014), allowing growers to sidestep land-related challenges like pollution, environmental rehabilitation, and zoning issues through the use of indoor vertical farming techniques (Anderson *et al*., 2012). Moreover, this technique would reduce the reliance on synthetic pesticides (Garg and Balodi, 2014).

Other advantages of vertical farming include year-round produce distribution, immunity to yield losses due to adverse weather, job creation in urban settings, water conservation, and reuse, and decreased food spoilage risks from mishandling. The utilization of controlled environments in vertical farming enhances its resilience against the effects of climate change (Germer *et al*., 2011). Crops in vertical gardens are typically more manageable for cultivation and harvesting, with lower susceptibility to diseases and pests (Utami *et al*., 2012). The absence of soil in vertical farming systems generally prevents weed growth, reducing labor costs in this aspect. Plants receive optimal aeration, and the visual appeal of the garden is enhanced through vertical farming practices. Comparatively, higher yields are often achieved with this method than with traditional farming practices. For example, Chinese cabbage yield using vertical farming reached 45 tons per hectare, surpassing the 10 to 25 tons per hectare range seen in field cultivation of the same crop (Utami *et al*., 2012). According to the opinion of Kannaujia *et al*. (2021), the benefits of vertical farming encompass increased net returns per unit area, accelerated growth leading to higher yields, reduced water and fertilizer usage, job opportunities, enhanced farmer incomes, continuous year-round production, environmentally friendlier processes compared to traditional methods, decreased risks of crop failures, minimized reliance on pesticides for pest control, progress towards nutritional security, and immunity to adverse environmental conditions. Vertical structures primarily cultivate plants that grow upright, are not sprawling, and bear fruits along their stems. These include vegetables like lettuce, tomatoes, cucumbers, bell peppers, mint, cilantro, spinach, strawberries, various herbs, and certain medicinal plants that demand minimal vertical space (Kannaujia *et al*., 2021).

## 2. Vertical farming types, techniques, and production systems

*Outdoor vertical farming type*

Vertical farming outdoors entails cultivating vegetables using vertical support systems constructed from readily available materials, such as bamboo structures supplemented with wires to assist the vegetables in climbing upwards (Kannaujia *et al*., 2021).

*Indoor vertical farming type*

Indoor vertical farming involves a range of permanent structures that support plant growth, typically within polyhouses, net houses, shade nets, and bamboo structures covered with plastic sheets. This method encompasses hydroponics, aeroponics, and aquaponics (Kannaujia *et al*., 2021). An indoor multilayer plant cultivation system meticulously manages all growth factors like temperature, light, carbon dioxide levels ($CO_2$), humidity, water, and nutrients to yield abundant, high-quality fresh produce consistently throughout the year, independent of natural light or outdoor conditions (Sharathkumar *et al*., 2020). Vertical farming involves growing crops or vegetables in vertically stacked layers or on vertical structures that promote upward growth, typically within a controlled environment tailored for optimal plant growth. It frequently employs soilless farming methods like hydroponics, aquaponics, and aeroponics (Kannaujia *et al*., 2021).

*Hydroponics*

Hydroponics entails cultivating plants without soil, with their roots submerged in nutrient-rich liquid solutions comprising vital macronutrients like nitrogen, phosphorus, and potassium, along with trace elements such as iron, manganese, and zinc. Inert materials like gravel, sand, sawdust etc. are used to support the roots in hydroponic systems (Fig. 1). By maintaining controlled environments and adhering to strict certification standards, hydroponic farms present a pragmatic method for sustainable food production by eradicating the necessity for harmful chemicals like pesticides. This innovative farming method is not just a concept but is actively being integrated into sustainable agriculture practices to meet the increasing global food demand (Debangshi, 2021). Hydroponics involves plants growing without soil, instead utilizing inert mediums like coco peat and nutrient-rich water solutions to support and nourish the roots, and can conserve about 70 percent more water than traditional farming methods (Bhanu Murthy *et al.*, 2022).

It presents a viable production alternative that vegetable growers can explore, with setups possible even in small spaces like a 400 ft² area or a small shed (USDA, 2016). In hydroponic systems, plant roots are immersed in a nutrient solution tailored to meet their nutrient requirement (Despommier, 2014).

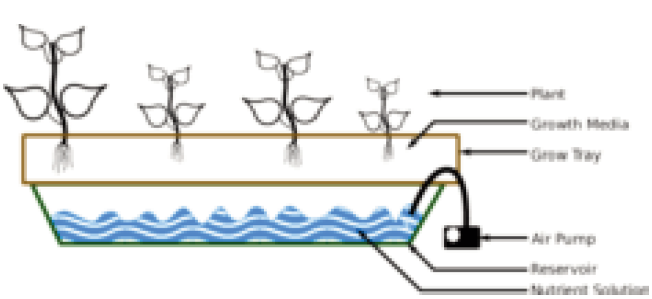


Fig. 1 - A model of hydroponics. Adapted from: https://images.app.goo.gl/jshegzQxE9uQnUk3A

*Aquaponics*

Aquaponics represents a type of hydroponics where plants are cultivated alongside aquatic organisms in a closed-loop system that emulates natural processes. A device for solids removal filters the nutrient-rich wastewater from fish tanks before channeling it to a biofilter, where harmful ammonia is converted into nutrient-rich nitrate. The plants absorb these nutrients, cleansing the wastewater before it returns to the fish tanks. Additionally, plants can absorb carbon dioxide ($CO_2$) from the air to perform photosynthesis, which is essential for their growth. In an aquatic environment like a fish tank or aquaponic system, fish release carbon dioxide into the water through respiration (Fig. 2). Therefore, in

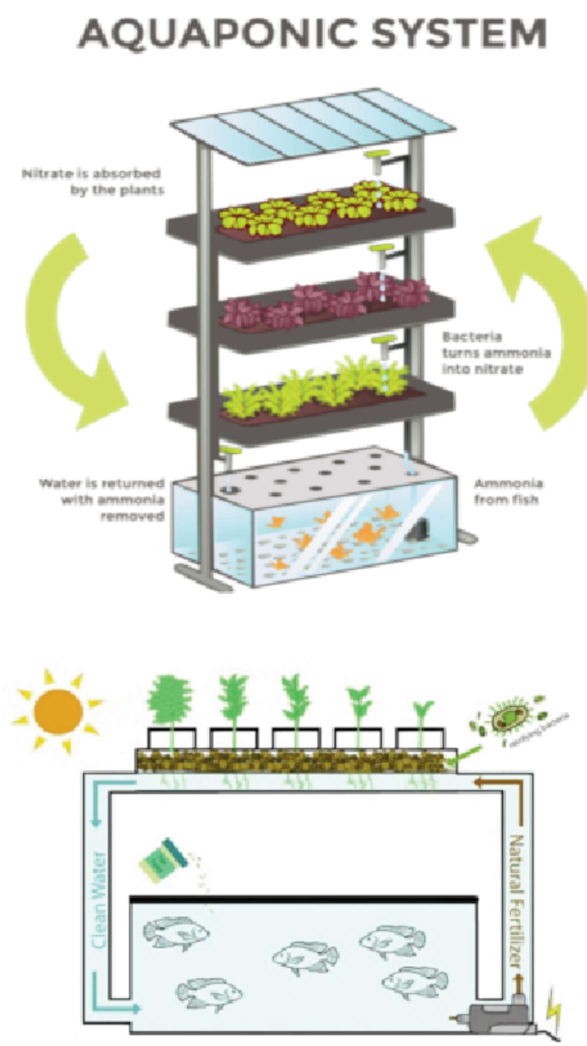


Fig. 2 - A model of aquaponics (Adapted from: https://images.app.goo.gl/6sKPJmTEfi1Z4MgZ7).

an aquaponic system or a similar setup where fish and plants coexist, it is important for the plants to uptake $CO_2$ from the fish to help maintain the balance of gases in the water and promote the well-being of both the aquatic life and the plants. Despite its aquacultural aspect, aquaponics is not as commonly employed as traditional hydroponics in commercial vertical farming setups, which typically focus on cultivating select fast-growing vegetable crops (Debangshi, 2021). Aquaponics functions as an ecosystem built on mutual relationships between plants and fish. The concept revolves around establishing a semi-self-sustaining system where fish waste nourishes plants in a vertical farming environment (Diver, 2021).

Notably, aquaponics utilizes only 2 percent of the water required in traditional farming, and operates as a closed-loop system with recyclable outputs, thereby generating minimal waste (McCollow, 2014). For instance, AeroFarms in New Jersey reportedly consumes 95 percent less water compared to field cultivation to produce equivalent volumes of leafy greens (Peters, 2015). Filtration poses a significant challenge for aquaponic businesses, as the accumulation of debris can endanger the fish and cause a chemical imbalance in water which is crucial for supporting plant growth (McCollow, 2014).

*Aeroponics*

Aeroponics originated from NASA's project in the 1990s, aiming to develop an efficient method for plant cultivation in space. Unlike hydroponics and aquaponics, aeroponics operates without a solid or liquid medium for plant growth. However, a liquid nutrient solution is being sprayed on plant roots in sprinkler form. It stands out as the most environmentally sustainable soilless cultivation technique, requiring no medium replenishment and consuming up to 90 percent less water than highly efficient traditional hydroponic systems. No growing medium is necessary for aeroponics, as the system is designed vertically, leading to energy savings as excess liquid naturally drains away due to gravity, unlike traditional horizontal hydroponic systems that often rely on water pumps to manage surplus solutions (Fig. 3). While aeroponic systems are not prevalent in current vertical farming practices, they are gradually gaining popularity (Debangshi, 2021). Aeroponics supports the growth of vegetables, flowers, and fruits, offering potentially higher nutrient quality and absorption of vitamins and nutrients compared to other methods (Birkby, 2016). Despite the use of modern pumps and control systems, aeroponics requires less automation.

These systems are favored over hydroponics for their water conservation benefits and reduced disease susceptibility (Boston, 2014). The vertical growth pattern in aeroponics makes it ideal for producing a large volume of plant materials in limited spaces, with plants either growing vertically in a tube-like structure or suspended in containers.

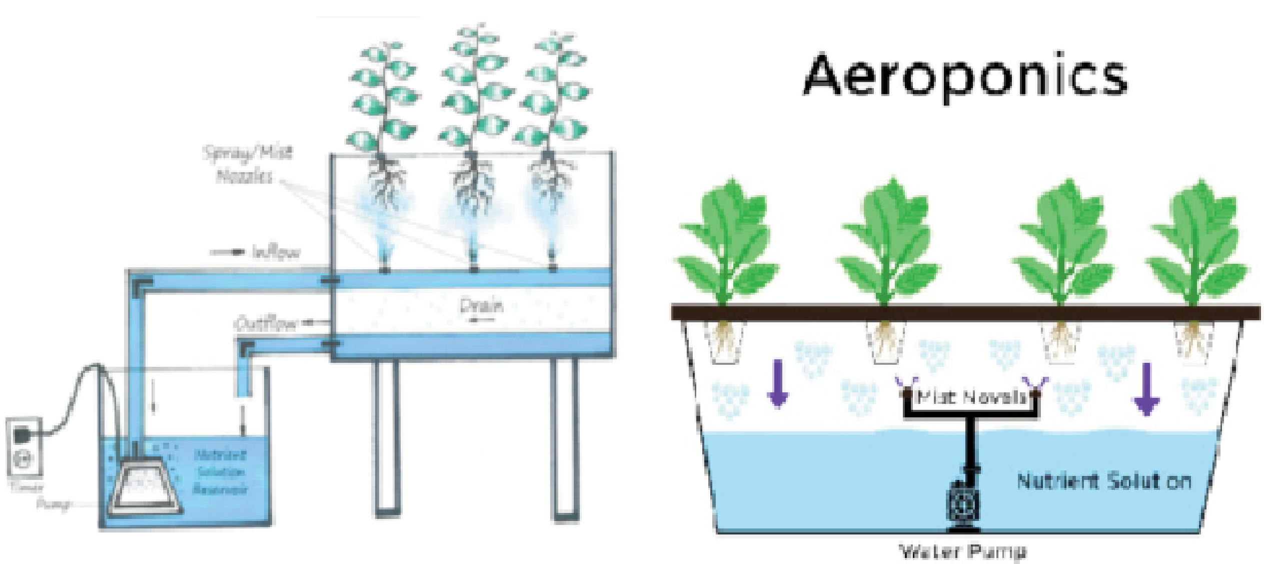


Fig. 3 - A model of aeroponics (Adapted from: https://images.app.goo.gl/9JCB4eRgYPya8vsa8)

## 3. What are the opportunities and importance of vertical farming for sustainable urban horticulture?

Globally, urban regions exhibit higher population densities compared to rural areas, accommodating 54 percent of the total population in 2014 (Fig. 4). The rapid economic growth over the last thirty years has coincided with a significant increase in the urban population. In 1950, urban dwellers constituted 30 percent of the global populace; projections indicate that by 2050, this figure will swell to 66 percent. With the world's population expected to approach nine billion by 2050, the role of vertical farming in fostering sustainable urban horticulture and ensuring food security has emerged as a pivotal topic for discussion. Urbanization entails a demographic shift where a larger share of a nation's populace resides in cities due to migration from rural areas to regions that subsequently witness declining populations, leading to escalated land utilization (Satterthwaite *et al.*, 2010). The repercussions of urbanization on agriculture are poised to revolutionize how food is distributed and marketed (Kennedy *et al.*, 2004). Notably, urban locales are witnessing a rising inclination towards the consumption of fresh produce such as fruits, vegetables, meat, and dairy (Agnes, 2014). Forecasts suggest that urbanization will amplify job opportunities in food processing, transportation, and retail sectors while diminishing agricultural employment (Cohen and Garret, 2010). Consequently, urban residents will be compelled to offer high-quality products for consumption or commercial purposes through urban agriculture to sustain their livelihoods (Redwood, 2009).

In the contemporary era, we are witnessing a swift surge in global population, particularly in developing regions like Africa, Asia, and South America.

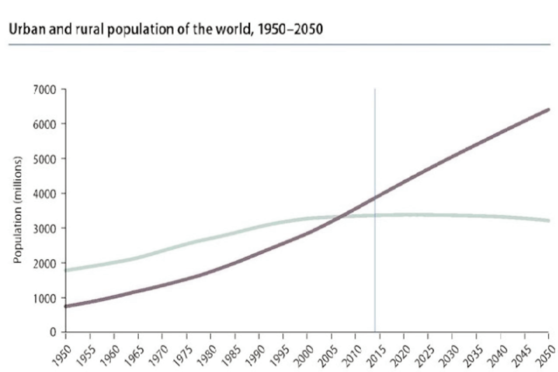


Fig. 4 - World urban and rural population, 1950-2050. Source, Nwosisi and Nandwani (2018).

Projections by United Nations indicate that by 2100, the global population is expected to surpass 21 billion individuals. UN estimations suggest that by 2050, 66 percent of the world's populace will reside in urban areas, with Europe reaching 82 percent urbanization (United Nations, 2017). The rapid expansion of the population invariably translates into heightened food requirements. Presently, 80 percent of the world's arable land is under cultivation, while the remaining 20 percent lies barren, its agricultural potential nearly squandered due to inadequate land management in recent decades (Eigenbrod and Gruda, 2015). The global population is swiftly escalating, alongside the pace of urbanization. UN projections from 2015 forecast a population increase exceeding double by 2050, urbanization trends continue to evolve, with more people moving to cities globally. By 2050, the United Nations projects that nearly 68% of the world's population will live in urban areas. As urban regions contribute to more than 70 percent of worldwide $CO_2$ emissions, resulting in pollution and negative environmental consequences, ensuring food security emerges as a critical issue in urban environments. As urban populations swell, the conventional cultivation of fresh fruits and vegetables faces challenges due to nutrient-deficient soil and limited usable land, posing a significant threat to the supply of fresh produce (Zaręba *et al.*, 2021). Vertical farming, a soilless agricultural technique for cultivating fresh vegetables, is swiftly gaining traction and holds a promising future. Researchers and scientists are exploring this method of farming as a viable option for urban dwellers.

Despite its longstanding presence, vertical farming remains relatively unknown to many, with only a minority having harnessed its potential for growing fresh produce. This innovative approach has the potential to significantly enhance food production while reducing the environmental impact of agriculture by utilizing less land, water, pesticides, and fertilizers, thereby enhancing overall efficiency (Barui *et al.*, 2022). The rising popularity of vertical farming globally is attributed to its efficient resource management and ability to yield high-quality foods. Particularly in regions with limited access to soil and water resources, vertical farming could revolutionize fruit and vegetable production. Across all crops, the use of vertical farming technology results in a substantial increase in yields. However, the degree of improvement varies significantly, with crops like potatoes and tomatoes showcasing the most potential for yield enhancement. Peas and spinach reflect minimal benefits from the vertical farming technology (Table 1). To combat issues like congestion, pollution, and escalating food prices, urban areas facing scarcity of land and high real estate costs must generate sufficient food to sustain their populations (Mir *et al*., 2022). Factors such as rapid urbanization, natural calamities, climate change, and indiscriminate use of chemicals and pesticides have collectively contributed to deteriorating soil fertility. Consequently, soil productivity has plummeted, soil health has deteriorated, and the available land per person has dwindled (Lal, 2015). Projections suggest that by 2050, with the global population expected to reach 8.9 billion, there will be a 50 percent surge in food demand, necessitating additional arable land that is simply not accessible (FAO, 2011).

The anticipated arable land per capita by 2050 is forecasted to be less than 0.20 hectares, marking a decline to less than one-third of the 1970 levels (FAO, 2011) (Fig. 5). The challenges posed by these issues pose significant threats to conventional soil-based agricultural systems, rendering food production a formidable task in the present day. To address these challenges, traditional soil-based farming methods need to be augmented with more efficient and environmentally sustainable modern farming practices (Lehmann, 2010). In transitioning to innovative vertical farming techniques, factors such as diminishing soil productivity, limited soil nutrient reserves, insufficient irrigation water availability, and the impacts of climate change must all be taken into account. Vertical farming methods, serving as an alternative to conventional soil-based farming systems, have the potential to serve as a supplementary solution in mitigating the scarcity of fertile arable lands and water resources (Texier, 2013).

Table 1 - Estimated yield of a vertical farm compared to traditional farming. Source: Barui *et al*., 2022

| Crops | Yield in vertical farming (tons/ha) | Field yield (tons/ha) |
|---|---|---|
| Carrots | 58 | 30 |
| Radish | 23 | 15 |
| Potatoes | 150 | 28 |
| Tomatoes | 155 | 45 |
| Pepper | 133 | 30 |
| Strawberry | 69 | 30 |
| Peas | 9 | 6 |
| Cabbage | 67 | 50 |
| Lettuce | 37 | 25 |
| Spinach | 22 | 12 |
| Total (average) | 71 | 28 |

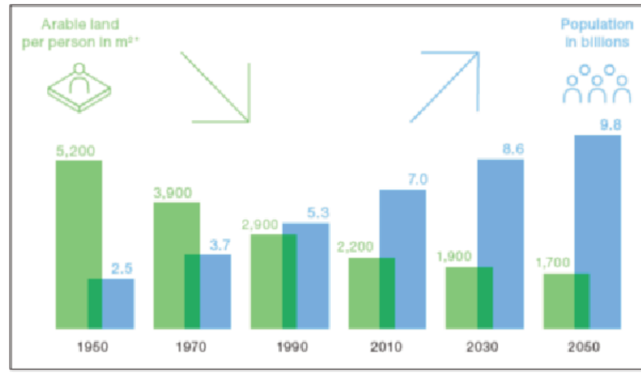


Fig. 5 - Scenario of global population and cultivable land with their projection up to 2050. Source: FAO (2011).

The human population, grappling with the impacts of climate change, must forge a new realm of spaces that ensure environmental sustainability and foster sustainable urban horticulture. In the future, the rise of vertical urban farms will increase crop production, lower costs, and improve the quality of food in urban areas. This will aid in reducing the harmful environmental effects of urbanization (Thomaier *et al*., 2015).

Vertical urban farms offer numerous advantages for the natural environment, including the autonomy of vertical crops from the polluted urban surroundings, aligning with the principles of sustainable development for environmental well-being, minimal water usage that enhances sustainable water management, and the potential utilization of organic waste generated (Despommier, 2013). Crucially, advanced vertical farming surpasses traditional farming in food production. Recent plant factory technologies can cultivate fresh, safe, and nutrient-rich produce year-round within cities, despite climate fluctuations, exhibiting high water and land efficiency while requiring less labor than traditional methods (Kozai and Niu, 2015). The proliferation of horticultural offerings in urban settings grants individuals more opportunities to engage with greenery and fosters community bonds. Many city dwellers, for instance, partake in activities like tending flower beds to enhance their city's green spaces and landscapes, showcasing how plants can cultivate communal ties. Moreover, these undertakings not only enhance the aesthetic appeal of cities but also significantly impact the well-being and quality of life of participants (Wakefield *et al*., 2007).

Vertical farming emerges as a promising strategy to address a range of Sustainable Development Goals (SDGs) established by the United Nations General Assembly in 2015, covering "good health and well-being, sustainable cities and communities, responsible consumption and production" (United Nations, 2020). Nature-related hobbies such as gardening and horticultural pursuits are renowned for their stress-reducing effects. Recent research underscores that engaging in gardening or horticultural activities can alleviate stress (Van den Berg and Cluster, 2011), boost self-esteem, nurture social connections (Cammack *et al*., 2002), and enhance cognitive well-being (Cimprich, 1993). Vertical farming is swiftly gaining prominence as a preferred cultivation method among various urban agricultural practices (Agrilyst, 2017). Vertical farming represents an advanced form of soilless cultivation that pushes the boundaries of traditional agriculture, evolving into a fusion of urban and rural practices. These vertical farms serve as hubs for the self-production of food, recreating ideal climatic conditions inside structures to support the growth of diverse plant varieties. Here, vegetables thrive without soil, drawing nutrients from water solutions under LED lighting systems. Supporters of vertical farming and urban horticulture emphasize that by functioning within controlled environments, these farms can protect crops from insect infestations and diseases, eliminating the necessity for pest control measures (Despommier, 2013). A key objective of vertical farming is to maximize crop yields per unit of land area utilized. However, when determining the optimal number of plants to cultivate within a given building space, careful attention must be paid to plant spacing. The density of plants is a critical factor in managing pests and diseases, as it affects the microclimate around the plants (Burdon and Chivers, 1982).

Achieving complete prevention of disease transmission would require impractically large plant spacing (Burdon and Chivers, 1982). Therefore, the quest for maximizing crop production per unit area must strike a balance between plant density and avoiding overcrowding for optimal crop growth and health. Even traditional open-field growers face mounting pressure to enhance productivity. The planet is showing signs of strain, with escalating disease pressures underscoring the critical need for sustainable solutions like vertical farming in regions striving for self-reliance. As we face the daunting challenge of feeding a burgeoning global population over the next two decades, the strategy involves harnessing space efficiently, expanding skyward, and repurposing existing urban areas (Kumar *et al*., 2018). Urban food security hinges on factors such as food availability, accessibility, and quality, all of which stand to benefit from the implementation of urban vertical farming techniques. Various gardening methods can significantly bolster the food security of communities and households. Whether at a personal or communal scale, cultivating food can enhance food and nutrition security across all economic strata (Kortright and Wakefield, 2011). The integration of urban horticulture in future city planning holds the promise of elevating food security levels, fostering a more balanced food distribution between rural and urban regions. Despite the advancement of global urban horticulture, rural agriculture will continue to play a pivotal role in ensuring global food security (Dubbeling *et al*., 2010). Vertical farming epitomizes sustainability, with the ability to stack farms vertically to amplify productivity per unit of land, thereby conserving arable land for alternative uses. Moreover, these farms eliminate transportation costs by bringing crops closer to urban markets, while also facilitating the recycling of energy and water within their structures. Additionally, the utilization of methane digesters can convert organic waste into energy, powering the operations within the building itself (Kumar *et al*., 2018).

## 4. Challenges in vertical farming systems

The study conducted by Jasim *et al*. (2016) revealed that the majority of vertical farms interviewed lacked systematic tracking of key metrics such as monthly energy and water usage, precise yield, waste management, air quality, and the extent of pesticide or fertilizer application. These deficiency poses significant obstacle in establishing a performance baseline for these operations. Light poses a critical challenge as light-emitting diodes must substitute natural sunlight, potentially leading to heightened energy consumption, operating expenses, capital outlay, and overall investment costs, particularly in large-scale commercial setups, thereby impacting profitability (Kretschmer and Kollenberg, 2011). Vertical farming primarily focuses on cultivating rapidly maturing vegetables and crops like herbs and salad greens. Slow-growing leafy vegetables and grains are less lucrative due to lower profitability.

Without natural insect populations, manual pollination is necessary in vertical farms, requiring additional labor and attention (Birkby, 2016). A key concern lies in the initial expenses associated with implementing vertical farming systems, encompassing costs for remote monitoring systems, automation technologies for stacking, climate control mechanisms, and other infrastructure (Barui *et al.*, 2022). According to Vashi and Dubei (2020), the potentials of vertical farming include catering to the rising demand for safe and organic produce, fostering community and hobby farming benefits, and repurposing historical structures that require management and restoration. Additionally, due to the diverse climatic and nutritional needs of various crops, mixed farming is impractical in vertical setups, and not all crops suitable for horizontal cultivation can thrive vertically. Meeting market or customer demands within specific timeframes poses challenges, as produce may mature ahead of or behind schedule, resulting in surplus yield from vertical structures that either go to waste or are undersold (Kannaujia *et al*., 2021).

Choosing a crop for vertical farming involves assessing two key factors: technical feasibility and market acceptance. Establishing and running a vertical farming system customized for a particular crop poses notable technical challenges, with the marketability of the produced goods being essential. While in theory, any crop can be grown vertically, the majority encounter notable technical and growth-related obstacles. Due to their small size, quick growth cycles, and minimal energy needs, several vertical farming systems specialize in leafy greens such as leaf lettuce, head lettuce, and herbs (Beacham *et al*., 2019). In contrast, energy-intensive crops such as large vining plants (e.g., melons) or tree fruits often require specialized designs different from standard vertical farming systems, making them less common in vertical farms. Companies specializing in vertical farming technologies play a key role in developing unique designs tailored to accommodate the specific needs of diverse crops in vertical farming systems.

## 5. Summary and future line of works

Vertical farming involves cultivating crops in confined areas where plants receive regular nutrients and water. Quick-growing green leafy vegetables such as mint, amaranthus, and lettuce thrive in vertical systems due to the accurate nutrients and water they get. This efficient growth results in high-quality produce and good yields, making vertical farming a promising solution for urban areas facing land scarcity and high food demand, aiming to combat pollution and escalating food prices. The outlook for vertical farming seems promising, particularly with the utilization of advanced technologies like hydroponics, aeroponics, and aquaponics.

These contemporary farming techniques are ideal for urban settings as they boost productivity significantly while vertical farms often utilize automation technologies such as sensors, artificial intelligence, and robotic systems to monitor and control factors like lighting, temperature, humidity, and nutrient delivery. This automation can reduce the need for constant manual intervention and monitoring. The decreasing availability of cultivable land in urban areas has worsened the difficulty of supplying fresh, high-quality vegetables. Hence, vertical farming emerges as an ideal alternative for cultivating fresh leafy vegetables and fruits in the times ahead. Further research into vertical farming is crucial to enhance production and lower operational expenses compared to traditional soil-based agriculture. To sustain urban horticulture, there is a pressing need to focus on extension programs to train farmers on vertical farming techniques and cultivate various crops in vertical structures. This education will be crucial in encouraging the extensive uptake of vertical farming techniques for a more sustainable urban food production system.

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