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Urban Greenhouse Establishment Strategies for the Cultivation of Vegetables

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ABSTRACT

The increasing trend of the global population increase and urbanization requires a parallel increase in agricultural production. Increased urbanization particularly demands for increased food supply, especially fruits and vegetables. Urban greenhouse establishment present a promising strategy for addressing food insecurity and sustainability in metropolitan areas. This review explores various methodologies and best practices for setting up and managing urban greenhouses dedicated to vegetable cultivation. Establishment of greenhouses requires strategic approaches, including site selection, structural design, micro-climate control systems, and sustainable practices. Optimal site selection considers proximity to consumers, accessibility, and integration with existing urban infrastructures. With systematic intervention, structural design maximizes space efficiency and ensures adequate light and ventilation. Importantly, advanced micro-climate control systems, such as automated temperature, humidity, and carbon dioxide (CO_2) regulation, are essential for year-round production of vegetables. Emphasis on sustainable practices, including Integrated Pest Management (IPM), water conservation through hydroponics, aeroponics and aquaponics systems, renewable energy utilization, and waste management, are crucial. This review paper presents case studies from diverse urban settings which demonstrate the successful application of these practices, highlighting benefits such as reduced food miles, enhanced food and nutrition security, and positive environmental impacts. It also suggests policy recommendations to support urban greenhouse initiatives, advocating for public-private partnerships, funding mechanisms, and regulatory frameworks to facilitate the adoption of urban greenhouses for vegetable production.

Keywords: Greenhouses, hydroponics, vegetable production, urbanization, urban farming

RÉSUMÉ

La croissance soutenue de la population mondiale et l'urbanisation exigent une augmentation concomitante de la production agricole. L'urbanisation intensifie en particulier la demande en denrées, notamment fruits et légumes. L'implantation de serres urbaines constitue une stratégie prometteuse pour répondre à l'insécurité alimentaire et aux impératifs de durabilité dans les

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métropoles. Cette revue examine les méthodologies et bonnes pratiques pour la création et la gestion de serres urbaines dédiées aux cultures légumières. La mise en place requiert des approches stratégiques intégrant la sélection du site, la conception structurelle, les systèmes de contrôle du microclimat et des pratiques durables. Le choix optimal du site considère la proximité des consommateurs, l'accessibilité et l'intégration aux infrastructures urbaines existantes. Avec des interventions systématiques, la conception vise la maximisation de l'usage de l'espace et assure un éclairage et une ventilation adéquats. Des systèmes avancés de contrôle microclimatique tels que l'automatisation de la température, de l'humidité et du CO_2, s'avèrent essentiels pour assurer la production sur toute l'année. Il est crucial de mettre l'accent sur la durabilité, incluant la lutte intégrée (IPM), économie d'eau via hydroponie, aéroponie et aquaponie, recours aux énergies renouvelables et gestion des déchets. Cette revue literaire présente des études de cas en environnements urbains variés qui illustrent l'efficacité de ces dispositifs tels que rla éduction des kilomètres alimentaires, la consolidation de la sécurité alimentaire et nutritionnelle et les effets environnementaux positifs. Des recommandations de politiques publiques sont formulées en faveur de partenariats public-privé, de mécanismes de financement et de cadres réglementaires propices à l'adoption de serres urbaines pour la production légumière.

Mots clés: serres: hydroponie ; production légumière ; urbanisation ; agriculture urbaine.

INTRODUCTION

Urbanization presents enormous opportunities for the global food markets (Tefft *et al*., 2017). However, the rapid urbanization with increased urban populations poses significant challenges to traditional agricultural production practices, including food and nutritional insecurity (Djan, 2023). Sustainable urban food production is urgently needed to supply humanity with sufficient food, an approach which should contribute to delivering fresh local food. Urban agriculture (UA), also known as urban farming (UF), is considered a potential solution for the emerging food crises associated with increased urbanization (Ebissa *et al*., 2024). Urban Agriculture is increasingly being adopted as a strategy to supply food for city dwellers. Besides, Urban Agriculture generates employment opportunities, while reducing environmental impacts through reduced transportation, packaging, and storage, thus strengthening cities' resilience (Gunapala *et al*., 2025). However, the growth of Urban Agriculture faces challenges related to land availability, planning, and the burden of meeting future food demands amidst climate change.

Urban farming involves growing, processing, and dissemination of food and other products through plant cultivation and rearing livestock in and near cities for feeding the urban societies (Mougol, 2000). It can be practiced either inside (intra-urban) or on the outskirts (peri-urban) of a town, city, or metropolis (Cabannes, 2012). Urban Agriculture is considered a remedy for possible future challenges that the global food system is expected to face (Daneshyar, 2024). Chaminuka *et al*. (2021) highlighted that UA is an opportunity to attain Sustainable Development Goals (SDGs, 2 and 3), which aim to end hunger and poverty while promoting household health and welfare. Urban Agriculture can significantly support several other SDGs, particularly Goals 11, 12, 14, and 15, which advocate for Sustainable Cities and Communities, Responsible Consumption and Production, Life below Water, and Life on Land, respectively (International Resource Panel, 2021; Pradhan *et al*., 2024; Thwaites *et al*., 2025). By integrating Urban Agriculture into urban planning, cities can enhance resilience against natural disasters, strengthen communities, and encourage civic involvement, aligning with Goal 11. Goal 12 promotes sustainable consumption and production by reducing the environmental footprint of conventional farming practices. Goals 14 and 15 focus on protecting life both on land and in water through the use of UA, which helps mitigate chemical runoff and supports sustainable land management. Furthermore, Garcia-Saravia *et al.* (2023) reported that circular economy strategies have a significant impact on the SDGS, particularly Goals 8 (decent work and economic growth), 12 (responsible consumption and production), and 13 (climate action), as they stimulate economic growth, promote sustainable production, and mitigate climate change, respectively. Although their influence on resource efficiency and social equity is indirect, it remains significant for Goals: 4 (quality education), 5 (gender equality), 10 (reduced inequalities), and 16 (Peace, justice, and strong institutions) (Garcia-Saravia *et al*., 2023).

Similarly, Drottberger *et al.* (2023) highlighted that some urban communities could achieve 70-80% fruit and vegetable self-sufficiency by utilizing various UA systems. Indeed, UA can play an essential role in community development by providing opportunities for social interaction, greater community cohesion and self-sufficiency, and engagement for young people in underserved neighborhoods (Leslie, 2012; Plunz *et al*., 2012). Currently, more than 55% of the world's population live in cities (Valavanidis, 2024). Hence, there is an urgent need to explore innovative solutions for producing sufficient amounts of fresh, nutritious vegetables for the high urban population (Tefft *et al*., 2017; Acharya *et al*., 2021; Mantzanakis and Christofilopoulos, 2023; Srinivasan and Yadav, 2023). To this end, the establishment of urban greenhouses, which utilize advanced agricultural technologies and sustainable practices, offers a promising avenue for cultivating vegetables in metropolitan areas (Nicholls *et al*., 2020; Chaminuka *et al*., 2021). Similarly, establishing UA can foster urban food system sustainability and resilience of the cities (Zou *et al*., 2022).

Utilization of urban greenhouses in urban farming can overcome several challenges associated with conventional farming, such as long supply chains, food spoilage, and high carbon footprints (Kulak *et al*., 2013). Additionally, there are significant social and gender benefits resulting from urban greenhouses, such as increasing social participation, building strong communities, and creating new urban and human-friendly space for environmental protection (Zareba *et al*., 2021). The fact that poor urban societies devote up to 85% of their revenue to food purchases, and 65% of women enroll in urban agriculture (Orsini *et al*., 2013) is evidence for the social significance of urban farming.Hence, UA effectively supports social and educational improvements by providing social inclusion and eradicating gender inequality. Additionally, evidence from cities around the world underscore the positive impact of UA on women, youth, and children (Mawois *et al*., 2011). Nevertheless, additional UA enterprises are being set up in underprivileged areas to supply localities with reasonably priced, nutritious produce (Leslie *et al*., 2012) by bringing food production closer to consumers. These farms, which are mainly greenhouses, reduce transportation costs and emissions, ensure fresher produce, and enhance the overall resilience of urban food systems (Zou *et al*., 2022). Although it may not be easy to compare the greenhouse gas emissions from urban greenhouses and vertical farming to traditional open-field farming (Molin and Martin, 2018), a 100-mile reduction in food transportation can cause a 5-10% reduction in carbon footprint (Mishra *et al*., 2024). Impressively, urban greenhouses can utilize vacant or underutilized spaces, such as rooftops, brownfields, and vertical spaces, thus contributing to urban revitalization and greening efforts as just green enough (Wolch *et al*., 2014; Gasperi *et al*., 2016; Zareba *et al*., 2021). Zareba *et al*. (2021) highlighted that Urban Vertical Farming (UVF) can perform many functions and bring diverse benefits such as reduction of city temperature, cleaning of pollutants, multiple harvests of food products and reduction of production costs to the inhabitants of cities. Here, UVF means the cultivation of crops, primarily vegetables, ornamentals, and herbs, on indoor shelf stacks by artificial light and fertilizer solutions with little soil and sunlight.

The ever-increasing world population in urban areas can sustain their food security partly by producing and providing supplemental nutritious foods grown using UVF. For instance, the production of mushrooms, hydroponic green fodder, vegetables, fruits and even poultry birds are either already in vogue or at advanced stages (National Academy of Agricultural Sciences, 2019). Moreover, UVF leverages various advanced technologies, such as hydroponics, aeroponics, aquaponics and other vertical stackings such as aero-farms and zip-grow to cultivate plants in multi-storey structures or small urban spaces (Swagat *et al*., 2023). *Hydroponics* involves growing of plants in the hydraulic system without soil or the growing of plants in the soilless system*,while aeroponics* is the growing of plants with no soil and very little water and nutrients in the form of mist or fog (plants suspended with roots misted in the air rather than submerged), and *aquaponics* – is an ecosystem that combines growing of plant and fish in a closed system using aquaculture and hydroponics. In this case, the fish waste is filtered and converted to nutrients, plants then absorb the nutrients and purified the water, as the purified water is finally returned to the fish tanks (Bambhaniya *et al*., 2023). Similarly, *aero-farms*, another smart vertical farming (SVF) innovation, is a technology that involves growing greens without sunlight or soil under a controlled environment, while the *zip-grow* is the growing of plants through conveyor rotation, automated nutrient delivery and Light Emitting Diode (LED) lighting and is mainly used by modern farmers (National Academy of Agricultural Sciences, 2019).

The increasing food demand in cities can be mitigated through UA, which is also projected to create more jobs in the future (De Bon *et al*., 2010). In cities of developing countries, UA is practiced in backyards of urban residences, public lands, as well as other public places, such as roadsides (Chaminuka *et al*., 2021). This negatively impacts the environment, urban infrastructure, and social welfare, which eventually affects the design and establishment of urban greenhouse policies and strategies (Ebissa *et al*., 2024). On the other hand, in developed countries, UA is designed and established based on different urban policy recommendations that have little impact on urban communities and environments (van der Schans and Wiskerke, 2012).

Among urban horticulture crops, vegetables grow easily in urban greenhouses using soilless culture, such as hydroponics, aeroponics, and aquaponics (Akintuyi, 2024). It is noteworthy that vegetables are rich sources of vitamins, minerals, fibres and antioxidants, which can lower mortality risks due to cancer, heart attack and other non-communicable diseases, and morbidity due to micronutrient deficiency and obesity (Acedo and Buntong, 2024). This notwithstanding, establishment of an urban greenhouse to cultivate vegetables is not as simple as traditional farming; it involves multi-integrated approaches (Eigenbrod and Gruda, 2015), including site selection, structural design, micro-climate control systems, and integrated sustainable practices such as renewable energy integration, energy efficiency measures, and smart grids. Site selection is critical for ensuring proximity to consumers, accessibility, and compatibility with urban infrastructures (FAO, 2013). Additionally, structural design must prioritize space efficiency, adequate light exposure, and ventilation to optimize plant growth. Similarly, advanced micro-climate control systems, including automated temperature, light control options [*e.g.*, movable screen systems like photosynthetic active radiation (PAR)], humidity, and CO_2 regulation, are essential for maintaining optimal growing conditions throughout the year (Solange *et al*., 2013). Sustainable practices of urban greenhouse are the cornerstone of greenhouse operations, emphasizing resource efficiency, food security, and environmental stewardship. For instance, soilless techniques such as hydroponics and aquaponics can significantly reduce water usage compared to traditional soil-based farming (Pomoni *et al*., 2023). Moreover, given the current decreasing availability of arable land and water, hydroponics is positioned to complement conventional farming techniques to support global food security (Naresh *et al*., 2024). Additionally, renewable energy sources, like solar panels and wind turbines, can power greenhouse operations as an alternative energy source for efficient energy management in agriculture, while effective waste management practices, such as composting and recycling, minimizes environmental impact (Majeed *et al*., 2023).

Generally, this paper aims to provide a comprehensive overview of the strategies for establishing and managing urban greenhouses for vegetable production. By examining successful case studies and analysing best practices, the paper highlights the potential benefits of urban greenhouses and offers practical recommendations for their implementation. By fostering collaboration between public and private sectors, supporting innovative funding mechanisms, and developing favourable regulatory frameworks, urban greenhouses can become a cornerstone of sustainable urban development and food and nutrition security.

Factors Affecting Urban Greenhouse Establishment for Cultivation of Vegetables. Producing fruits and vegetables in greenhouse urban farming creates a closed-loop, self-sufficient business model, and functions as a distributing hub for the local communities (Likitswat, 2021). For instance, rooftops of schools, hospitals, hotels, prisons, supermarkets, and shopping malls are suitable for the establishment of greenhouses through hydroponic systems (Caplow *et al*., 2010). Currently, the establishment of greenhouses is rapidly gaining popularity as progressive farmers get more accustomed to the modern available technologies (Dwasi, 2017; FAO, 2017). Urban greenhouses offer a transformative solution to modern agricultural challenges by providing a controlled environment, conducive to year-round cultivation and optimized crop production. However, their successful implementation requires meticulous planning, strategic execution, and management (Nasiri, n.d).

Several critical factors influence the successful establishment and operation of urban greenhouses for the cultivation of vegetables (FAO, 2017). One of the primary considerations is the availability and cost of land or space within urban areas. High real estate prices and limited space can pose significant challenges, necessitating creative solutions such as utilizing rooftops, vacant lots, and repurposed buildings (Daneshyar, 2024; Ranjan and Sahoo, 2024). The local climate and weather patterns also play a crucial role, as they determine the types of micro-climate control systems (FAO, 2013) needed to maintain optimal growing conditions year-round in the greenhouse. Conversely, the greenhouse microclimate is seemingly affected by the form and orientation of the greenhouse, the direction of the wind, the covering material, and the use of an insect-proof screen. All these factors can have an impact on the overall amount of solar radiation, the thermal properties, and the internal flow pattern of the greenhouse micro-climate (Li *et al*., 2018). Hence, regulatory and zoning laws can either facilitate or hinder greenhouse projects, making navigating local policies and obtaining necessary permits essential (Bakewell, 2003). Indeed, economic factors, including initial capital investment, operating costs, and potential market demand for locally grown vegetables, must be carefully analyzed to ensure financial viability.

To sum it up, access to greenhouse resources such as water, energy, and sustainable agricultural inputs are other critical factors, as skilled labourers can manage and operate the greenhouse efficiently. Community engagement and support are vital, as urban greenhouses often rely on public interest and participation for long-term success. Addressing these factors through strategic planning and collaboration can significantly enhance the prospects of urban greenhouse initiatives, contributing to sustainable urban agriculture and food security. Generally, urban vegetable greenhouse establishment strategies represent a pivotal step towards achieving resilient and sustainable cities. By leveraging innovative technologies, sustainable practices, and community involvement, these initiatives enhance food security and promote environmental health and social well-being in global urban areas.

Site selection for urban greenhouses. Selecting the optimal site for urban greenhouses is crucial to the success of vegetable cultivation (FAO, 2013, 2017). Proximity to consumers is crucial, ensuring the produce remains fresh and minimizing transportation costs. Urban greenhouses should ideally be located in areas with easy access to transportation infrastructure to facilitate the efficient distribution of vegetables within the city. The integration with existing urban infrastructure, such as utilizing vacant rooftops, repurposing abandoned lots, or incorporating vertical farming systems, can significantly maximize space utilization and enhance the urban landscapes (Swagat *et al*., 2023). Additionally, the chosen site must have adequate exposure to sunlight or the potential for supplemental lighting to support healthy green vegetable growth. Assessing the structural integrity of potential sites, especially for rooftop installations, is essential to ensure they can support the greenhouse's weight and operational needs. Furthermore, accessibility to essential resources such as water and energy, as well as considerations for waste management, are critical for the sustainable operation of urban vegetable greenhouses. Thoroughly assessing the available space and suitability for cultivating vegetables ensures that the chosen site can support the greenhouse's structure and operational needs. Hence, urban greenhouse projects can be strategically positioned to thrive, contribute to local food security and sustainable urban development. Different urban farming systems and designs are presented in Figure 1 (a-d). There are different types of protected greenhouse structures (Figure 2). Rooftop greenhouses facilitate the growing of fresh produce near consumers, which significantly cuts down transportation distances and lowers carbon emissions (Figure 3). This localized food system boosts food security by ensuring urban residents have access to nutritious and affordable food while also decreasing dependence on fragile rural supply chains.

Structural designs used for the establishment of urban greenhouses. Urban greenhouses are designed to create and maintain an environment suitable for plant growth in order to supply food to cities. They vary widely in size and design, ranging from small backyard structures to large commercial operations. These designs enable provision of fresh vegetables and ornamentals year-round (Teitel *et al*., 2012).

a) Geodesic greenhouse design for vegetable production (*Source*: Getty images, 2023)

b) Vertical vegetable farming with white and red Light-emitting diode (LED) lamps offers the use of plant-related radiant energy [*Source*: Ranjan et al. (2023)]

c) Arch-shaped multi-span greenhouses with single and double roof ventilators [*Source*: FAO (2013)]

d) Urban greenhouse including rooftop farming (*Source*: Getty images, 2023)

Figure 1. Different urban farming systems and designs: grew salad greens year-round in a closed-loop system (*Sources*: Eigenbrod and Gruda, 2015; Mantzanakis and Christofilopoulos, 2023)

They are typically made of glass, rigid and transparent plastic, allowing sunlight to enter and trap heat inside (Figure 4 a-d). They are also used to extend the growing season in colder climates or to provide specialized conditions for plants that require specific temperature, humidity, or light levels (Nasiri, n.d). The structural design of urban greenhouses must prioritize space efficiency and ensure optimal growing conditions for vegetable farming.

Efficient layout and space utilization are crucial for maximizing production in limited urban spaces.Adequate light exposure and ventilation are essential for plant health and productivity, requiring thoughtful design of the greenhouse's orientation and structural components. Indeed, material selection should balance durability, cost, and environmental impact. Moreover, modularity and scalability are essential considerations, allowing the greenhouse to adapt to changing urban environments and expanding demand (Figure 1).

One popular urban greenhouse design is rooftop greenhouses (RTGs) (Figure 3), which utilizes otherwise unused rooftop spaces on urban buildings, providing insulation benefits and reducing the urban heat island effect. The RTGs can be permanent or temporary designs treasured on various building types, including commercial, industrial, and residential, that utilize different technologies, such as hydroponics, aeroponics, aquaponics, vertical farming (VF), etc., thus, allowing for efficient use of space and resources (Drottberger *et al*., 2023). These structures must be lightweight yet robust, often incorporating aluminum frames and rigid plastic (polycarbonate panels) to balance strength and light transmission. Another innovative design is the VF, which uses stacked layers to grow plants in a compact footprint (Swagat *et al*., 2023). This design is particularly advantageous in densely populated cities with limited horizontal space. VF can be defined as cultivating crops, primarily vegetables, ornamentals, and herbs, on indoor shelf stacks with artificial light and fertilizer solutions with little soil and sunlight. This farming often incorporates hydroponic and aeroponic systems to enhance water and nutrient efficiency (Figure 4b).

Additionally, geodesic dome greenhouses (Figure 1a) are gaining popularity for their structural integrity and ability to withstand harsh weather conditions while providing excellent light diffusion. Modular greenhouses, designed with interchangeable components, offer flexibility and scalability, allowing urban farmers to expand or reconfigure their growing spaces as needed. Each design must ensure adequate light exposure, ventilation, and temperature control to foster healthy plant growth.

Advanced technologies, such as automated shading systems, retractable roofs, and micro-climate control systems, are often integrated to optimize the growing environment. By leveraging innovative structural designs, urban greenhouses can effectively utilize available space and resources, supporting sustainable vegetable cultivation in urban settings.

Likitswat (2021) highlighted that a short investigation of urban farming and greenhouse design should focus on resource management, such as land organization and development, material and cost, cultivating and post-harvesting strategies, marketing and branding, and smart farming as well as technology management systems. Therefore, planning and designing different urban greenhouse structures to cultivate vegetables is indispensable to supply sustainable food to urban communities.

Figure 2. Types of protected greenhouse structures: polycarbonate polyhouse, polyhouse (fan-pad) and net house (from left to right) (*Source*:(ICAR-Central Institute for Sub-tropical Horticulture, 2015).

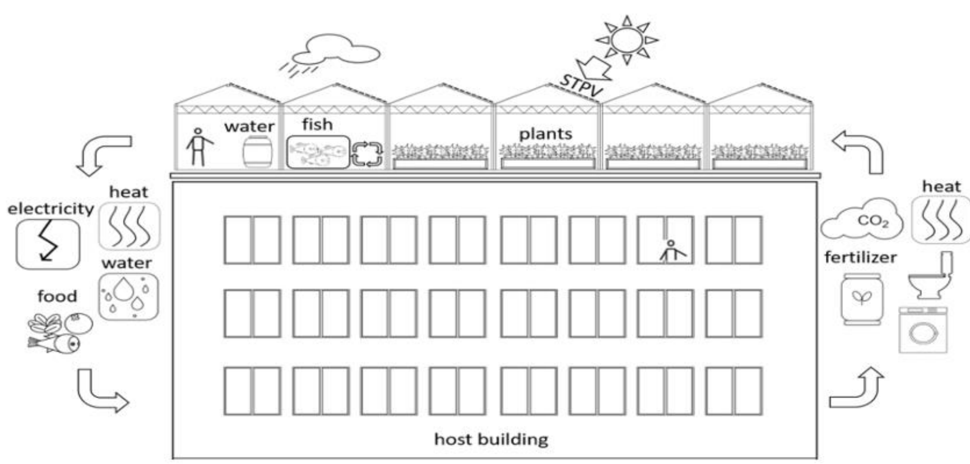

Figure 3. Integrated rooftop greenhouse (IRTG), using heat and respired CO2 from host building and delivering electricity, heat, water, and food to host building (*Source*: Drottberger et al., 2023)

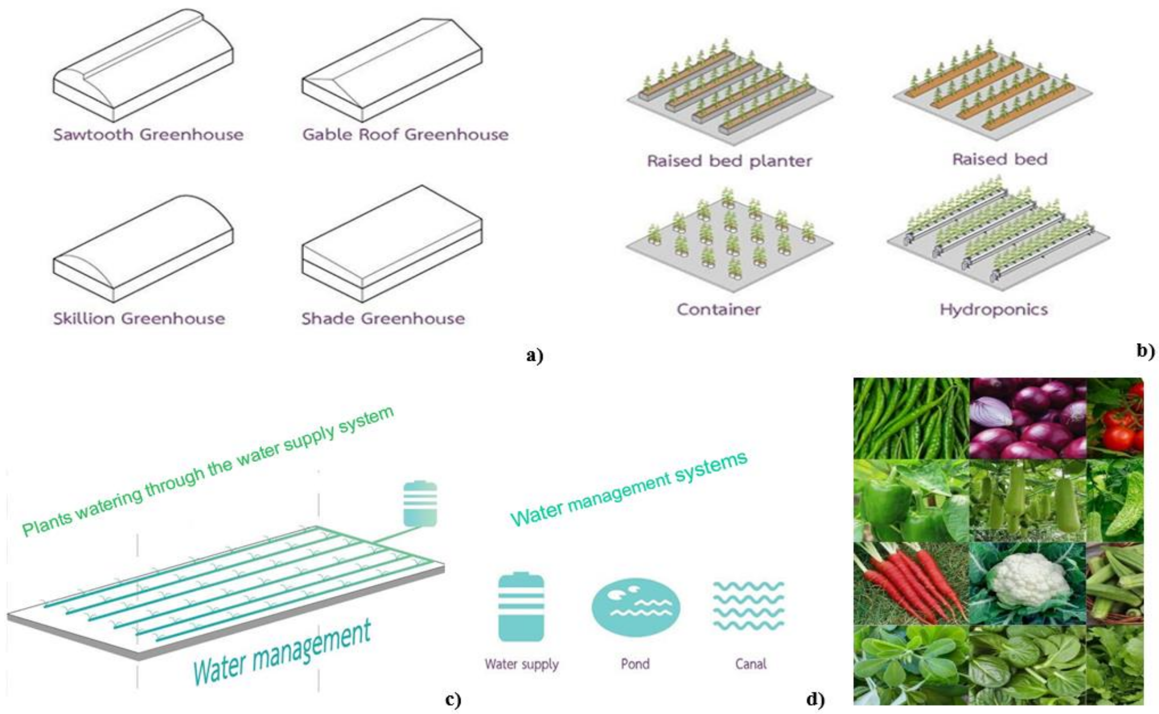

Figure 4. *Example of greenhouse design and systems: **a)** greenhouse structure, **b)** growing techniques, **c)** water management systems and **d)** selection of preferable vegetable types (Source: Likitswat (2021) and Getty images).*

Micro-climate control systems. Micro-climate control systems are integral to the success of urban greenhouses, as they ensure a stable and optimal growing environment for vegetables regardless of external weather conditions. For instance, temperature regulation is paramount, as most vegetables require specific temperature ranges to thrive. This can be achieved using heating and cooling systems and insulation materials that maintain the desired internal climate. In light of these systems, the micro-climate of the urban greenhouses is influenced by the design parameters of the greenhouses, such as the form, size, location, stature, position of ventilation, direction of wind blowing, and the type and variety of covering materials (Li *et al*., 2018). Urban greenhouse productivity can be increased via additional lighting, such as light-emitting diodes (LEDs), which are capable of precise and quick dimmability tailored to the individual needs of each species (Mosharafian *et al*., 2021) (Figure 1b). Humidity control is equally important to prevent mold, mildew, and plant diseases, often managed through ventilation systems, dehumidifiers, and misting systems. It is known that CO_2 enhances photosynthesis and accelerates plant growth. Thus, in urban greenhouses, CO_2 management is a key component of the micro-climate control strategy. Advanced automated monitoring and control systems allow for precise adjustments, utilizing sensors and computer algorithms to regulate real-time temperature, humidity, and CO_2 levels in urban greenhouses (Wacas, 2023; Vijaya *et al*., 2025). These systems not only improve efficiency and reduce labor costs but also enable year-round production and cultivation of vegetables by creating an ideal micro-climate. Besides, incorporating renewable energy sources, such as solar panels or geothermal systems, can further enhance the sustainability of these micro-climate control systems. By implementing sophisticated micro-climate control technologies, urban greenhouses can achieve high productivity and ensure the consistent nutritional quality of vegetables (He and Qin, 2022).

Sustainable practices in urban greenhouses. Sustainability is a cornerstone of urban greenhouse establishment strategies, ensuring that vegetable cultivation is environmentally responsible and economically viable. Water conservation is a primary focus (Figure 4c), with advanced techniques such as hydroponics, aquaponics, and drip irrigation significantly reducing water usage compared to traditional soil-based farming (Carroll *et al*., 2023; Naresh *et al*., 2024). These systems recycle water and nutrients, minimizing waste and enhancing efficiency.

Renewable energy utilization, including solar panels, wind turbines, geothermal systems can be used for sustainable greenhouse operations, reducing reliance on fossil fuels and lowering carbon footprints. Effective waste management practices are essential, with composting and recycling programs turning organic waste into valuable soil amendments, thereby reducing landfill contributions. Moreover, another indispensable sustainable practice during the cultivation of vegetables in the urban greenhouse is integrated pest management (IPM). This employs every available method of pest control, followed by the incorporation of suitable measures that deter the growth of pest populations, maintain the use of pesticides and other interventions at economically viable levels, and reduce hazards to the environment and human health (Santiago, 2019). Hence, IPM strategies reduce the need for chemical pesticides, promoting a healthier ecosystem and safer produce. Additionally, sustainable practices extend to selecting building materials, growing media (soilless culture), and growing containers, which should be made available to growers and favor recycling or locally sourced options that reduce environmental impact. By prioritizing these sustainable practices, urban greenhouses can contribute to food security and promote a more resilient and eco-friendlier urban environment. Through thoughtful structural design (Figure 4a) and innovative technologies, urban greenhouses can serve as models of sustainability, supporting the cultivation of fresh, healthy vegetables while preserving vital natural resources.

Multi-Scale Urban Farming Greenhouses: Case Studies. Vegetable production is the most popular component of urban food production, which contributes to global food security, with potential yields of up to 50 kg per m^2 per year (Eigenbrod and Gruda, 2015). The yield of vegetables can be highly increased by introducing protected cultivation or vertical farming. In one study, the yield of lettuce under vertical farming was 80-90 kg per m^2 per year, while it was only 3-4 kg per m^2 per year when produced under traditional farming (Mishra *et al*., 2024). In another instance, a 100 times increase in yield per unit area of lettuce was achieved by one farmer in Japan after shifting from traditional farming to vertical farming (Masyk and Fritz, 2017). It must be noted that the potential of protected agriculture, in general, and vertical farming, in particular, is dependent on the greenhouse infrastructures and the number of storeys utilized. In Kuwait, for instance, the average potential yield for tomato, potato, green pepper, carrot, lettuce, and cabbage was estimated to be more than 2,400 kg per m^2 as opposed to the actual yield of 4.7 and 7 kg per m^2 in open fields and protected agriculture, respectively (Abdullah *et al*., 2021). According to Zareba *et al*. (2021), assessing case studies of successful urban greenhouse VF projects provides valuable insights into effective strategies and innovative approaches, including the Forest City (Malaysia), Sunqiao (China), Gotham Greens (New York), Aero Farms (USA), and Chaise Urbaine (Strasbourg, Europe). Similarly, the rooftop greenhouse project in New York City demonstrates how urban farming can thrive in densely populated areas by utilizing rooftop spaces. The suitability of RTGs can be analyzed by using the combination of analytical hierarchy process (AHP) and geographic information systems (GIS) (Kil *et al*., 2023).

According to Drottberger *et al.* (2023), some cities have shown a potential for self-sufficiency of up to 70–80 % in fruits and vegetables by exploiting a combination of UA systems. Gould and Caplow (2012) highlighted that 1 ha of rooftop vegetable farm has the potential to save 20 ha of rural land in the USA, where each hectare can save 74,000 tons per year of fresh water on average. Similarly, they found that the environmental impacts of growing tomatoes in the urban greenhouse indicated that urban greenhouse utilizes 16% of freshwater compared to conventional farms, while avoiding pesticides and reducing GH emissions by 60% (Drottberger *et al*., 2023). Furthermore, the estimation of CO_2 emission when the greenhouse is integrated with the building heating systems and onsite solar power further diminishes to 1000 tons of CO_2 emissions annually compared to conventional greenhouses (Gould and Caplow, 2012). A single acre of BrightFarms greenhouse in Chicago could yield approximately 230,000 kg of produce, capturing 20 million liters of rainwater, mitigating about 740 tons of CO_2, and avoiding 195 kg of pesticides annually (Gould and Caplow, 2012).

Nicholls *et al*. (2020) highlighted that urban gardens and allotments in and near cities soffer significant contributions to feeding the world and are relatively favourable for some ecosystem services, such as supporting healthy soils. Such an initiative addresses local food insecurity, contributes to urban greening efforts, and reduces the city's carbon footprint by minimizing transportation distances and environmental pollutants. In Singapore, the Sky Urban Vertical Farming System (SUVFS), also known as the A-Go-Gro VFS, represents a pioneering approach to vertical farming in a highly urbanized environment. The Sky Greens is the world's first large-scale vertical farm, which began commercial operations in 2012 in Singapore (Chole *et al*., 2021). It is a hydraulic-driven VF in which vegetables are grown on shelves from the bottom to the top throughout the day to deliver sunlight and water for growing plants (Zareba *et al*., 2021). A Go-Gro vertical farming has a 9m height with three storeys and is housed in protected outdoor greenhouses. It has the potential to cultivate tropical leafy vegetables cultivated all year round with significantly higher yields than traditionally grown plants. The products are also definitely safe, high in quality, fresh and delicious. This vertical greenhouse maximizes land use efficiency, incorporating advanced hydroponic systems and automated micro-climate control technologies. When dwarf varieties suitable for VF are used, a 30-storey vertical farm of 2 hectares can produce an amount that parallels 970 hectares under traditional farming (Masyk and Fritz, 2017). This showcases how VF can produce a significant number of vegetables in a limited footprint, meeting the demands of urban populations for locally grown, fresh produce. Similarly, in Shanghai, China, a new model of urban farming, known as the Sunqiao urban agricultural district, is set to introduce vertical farming (VF) to the country's largest city (Zhou, 2024; https://cityfarmer.info/china-sunqiao-urban-agricultural-district). Here, vegetables are grown vertically in the form of skyscrapers using hydroponic and aquaponic systems. Over 56% of Shanghai's diet depends on leafy vegetables, which do not require specific attention and can easily grow in urban farming systems (Zareba *et al*., 2021).

Additionally, the Lufa Farms (LF), the world's first commercial RTGs, located in the Ahuntsic quarter of Montreal and the Gotham Greens (GG) project in Chicago (Meier *et al*., 2011) illustrate the integration of high-tech greenhouse technology with sustainable practices. By utilizing renewable energy sources and efficient water management systems, GG produces premium-quality vegetables year-round for local markets. These case studies highlight diverse strategies for overcoming urban challenges and maximizing the benefits of urban agriculture, serving as models for future urban greenhouse initiatives worldwide. On the contrary, the remaining waste products obtained from the greenhouses are transferred to biogas plants located in the neighborhood for composting, which later, deliver energy to support the plantation in working effectively in the greenhouse (Gioulounta *et al*., 2023).

Nowadays, there are buildings designed by World Food that are near offices and restaurants, for selling vegetables and fruits in-door farms. For instance, Chetwood Architects' proposed design to transform London Bridge into an urban vertical farm with solar-powered spires topped with wind turbines to feed the local organic market is an intriguing option for extremely crowded cities. In this concept, organic farms are situated on vast platforms that incorporate solar water heating, rainwater collection, and greywater treatment (Zareba *et al*., 2021).

Policy Recommendations

The global trends, such as increased population, climate change and resource scarcity, are among the major challenges for the future. These challenges, together with the uncertainties of urban agricultural practices, need special attention in cities. Therefore, different plausible narrative scenarios for 2030 aim to stimulate and raise awareness among policymakers, researchers, investors, and societal actors on the opportunities ahead (Mantzanakis and Christofilopoulos, 2023). Hence, effective policy frameworks are crucial for supporting the establishment and expansion of urban greenhouses, enhancing their contribution to sustainable urban development and food security. To enhance sustainability, urban horticulture must be integrated into urban planning and supported through policies (Eigenbrod and Gruda, 2015). Advocates and policymakers are instituting policies to support UA (Leslie, 2012), and public-private partnerships (PPPs) can play a pivotal role in leveraging resources and expertise across sectors. Governments can incentivize these partnerships through grants, subsidies, and tax incentives, encouraging collaboration between urban planners, agricultural experts, and technology innovators.

According to Cabannes (2012), lack of access to financial services is a significant bottleneck for most small-scale urban farmers to maintain and expand their capacity and activities, and more generally, in the potential for scaling up affordable food production in cities. Hence, financial support mechanisms are crucial for mitigating the initial capital costs associated with greenhouse construction and operation. Governmental or non-governmental organizations can provide grants or low-interest loans tailored, explicitly, to urban greenhouse projects, facilitating access to funding for infrastructure in integrated urban agriculture, equipment procurement, and operational expenses. Moreover, targeted subsidies for renewable energy adoption and water-efficient technologies can incentivize sustainable practices within urban greenhouse operations, reducing operational costs and environmental impacts.

Regulatory frameworks and zoning laws need to be updated to accommodate and support urban agricultural initiatives, including greenhouse installations (Leslie, 2012). Flexible zoning regulations can facilitate the repurposing of urban spaces for agricultural use, allowing for the integration of greenhouses into diverse urban landscapes while ensuring compliance with safety and environmental standards. Streamlined permit processes and clear greenhouse construction and operation guidelines are essential to minimize bureaucratic hurdles and expedite project implementation. Moreover, urban planners should consider UA, such as open or indoor urban greenhouses, VF and rooftop farming, as integral parts of cities so that residents can access fresh produce within their vicinities. To make UA sustainable, governments can encourage private companies and entrepreneurs to invest in urban farming by providing access to land, having green building regulations, land protection, facilitating loans, and establishing local markets (Dubbeling *et al*., 2016).

Community engagement and education programs foster public awareness and support for urban greenhouse initiatives. Governments and organizations can collaborate to implement outreach programs that educate communities about the benefits of locally grown produce and sustainable agricultural practices. By promoting consumer awareness and participation in UA, these programs can strengthen local food systems and enhance community resilience.

CONCLUSIONS

The rapid growth of urban populations and increasing food insecurity necessitate innovative agricultural solutions. Urban greenhouses present a pivotal solution for addressing contemporary food security challenges, sustainability, and urban resilience. Cities can foster local food production while minimizing environmental impacts by strategically integrating vegetable cultivation into urban landscapes through innovative structural designs, advanced micro-climate control systems, and sustainable practices. The case studies examined in this review underscore the versatility and effectiveness of various greenhouse models, from rooftop installations in New York City to Vertical Farms in Singapore (Sky Greens), demonstrating the adaptability of urban agriculture to diverse urban settings. Effective policy frameworks, including public-private partnerships, financial incentives, and social, gender-inclusive and supportive regulatory environments, are critical in facilitating the widespread adoption of urban greenhouses. Establishing small-scale and large-scale urban greenhouses for cultivating vegetables promotes access to food availability nearby and healthy nutrition in densely populated urban areas. Remarkably, fresh vegetables give cities a pleasant, fresh environment and decoration. Therefore, by empowering communities, enhancing food security, and promoting sustainable urban development, urban vegetable greenhouses ensure fresher, healthier produce for urban populations and contribute to a greener environment and a more resilient future for cities worldwide.

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DECLARATION OF CONFLICT OF INTEREST

The Authors declare No Conflict of Interest in this paper.

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