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Residential Rooftop Urban Agriculture: Architectural Design Recommendations

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Abstract: It is evident that, due to population growth, future urbanization and urban growth are inevitable. It is estimated that the food supply demand of future urban centers will grow, which will place an additional burden on the agriculture sector to produce more food. It is projected that securing the food supply chain for future urban centers will be a challenge. Urban agriculture can be regarded as a remedy for possible future challenges that the global food system will face. It might be able to reduce the future burden on the agriculture sector. This research proposes that urban rooftop agriculture, as a subset of urban agriculture, can produce local fresh food in dense urban environments. The principal aim of this research is to suggest a series of design recommendations for architects interested in designing residential buildings capable of rooftop food production. This research attempts to highlight the specific design recommendations and the principal limitations regarding designing residential rooftop farms. To extract the data for developing the proposed design recommendations and limitations, a review of the literature within the fields of urban agriculture, building-integrated agriculture, and horticulture was conducted. Based on the literature review results, this research suggests that the following three types of farming methods can be developed on residential rooftops: (1) open-air rooftop food production, (2) "low-tech" rooftop greenhouses, and (3) "high-tech" rooftop greenhouses. In addition, factors that can be considered principal limitations are suggested. In sum, this research proposes that current and future residential buildings can be designed so that their rooftops are utilized as farms. In this way, such buildings can contribute to delivering local fresh food to current and future metropolitan dwellers.

Keywords: residential rooftop farms; building-integrated agriculture; urban agriculture; controlled-environment agriculture; soilless farming

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1. Introduction

Currently, metropolitan areas host more than half of the globe's population. By 2050, approximately two-thirds of the global population is projected to reside in urban areas. At present, the globe is experiencing unparalleled urban growth [1–4]. The food supply demand in urban areas will further grow, which will place stress on the already overloaded agriculture sector and rural areas to produce more food [5,6]. Securing the supply chain of fresh vegetables and fruits for future urban areas is expected to be a challenge. Due to the growing food demand, alimentation will become a major issue in future urban centers [7–9]. Threats to future food production are multifold, with frequent and intense events linked with human-caused climate change, such as elevated temperatures, droughts, floods, tropical cyclones, forest fires, and rising sea levels, and the negative effect of industrial farming on ecosystem services such as soil quality degradation, water pollution, and loss of biodiversity and wildlife [10–12]. It is projected that the impact of climate change will increase food production variability and uncertainty in crop yield [13]. Population growth, meat and dairy consumption, and biofuel consumption will put additional demand on future crop production [14–17]. According to projections, to satisfy these rising demands by 2050, global agricultural production may need to increase by 60% to 110% [15,17–19]. There is a growing concern about how to feed the future population sustainably [20,21].

Urban agriculture can be regarded as a remedy to possible future challenges that the global food system will face [8,22–27]. Since urban growth is unavoidable, innovative approaches such as urban agriculture can contribute to delivering fresh, local food to future urban centers [25,28–30]. It might be able to reduce the future burden on the agriculture sector. It might be a solution to inadequate or unhealthy access to food in urban areas [25,30,31]. Open-air cultivation in line with controlled-environment agriculture can contribute to future cities' year-round vegetable and fruit production [7]. It has been suggested that future cities might have the potential to be self-reliant on food [32,33]. Future environmental issues such as the lack of arable land, water scarcity, soil and air contamination, population growth, and the high cost of transportation might put pressure on future cities to be self-sufficient in terms of food production. In this vision, future cities might incorporate community gardens, home gardens, roof gardens, balcony gardens, windowsill gardens, indoor gardens, school gardens, and aquaculture in addition to soilless systems in controlled environments to be self-reliant in food production [25,32,33].

Within metropolitan areas, a general awareness of local food production has led to the growth of urban agriculture [34,35]. Urban agriculture development within metropolitan areas can improve local food production [36]. Urban agriculture is an industry that is either within or on the periphery of urban areas. It consists of farming, horticultural, and agricultural practices usually carried out on small areas such as vacant lands, community gardens, backyards, front yards, balconies, windowsills, and rooftops. It involves growing, processing, and distributing various edibles and non-edibles to metropolitan dwellers. It mainly utilizes resources, products, and services available in urban areas. It aims to supply locally produced food to urban areas while recycling city waste and natural resources [24,37–42].

Urban agriculture has economic, social, and ecological significance [29,43,44]. Concerning the economic aspects, it might contribute to the following: It improves the local economy by creating jobs [6,45]. It can generate income for low-income families. It can contribute to poverty alleviation [6,46]. Cultivating food within urban centers can reduce food transportation energy and cost [25,47,48]. It can create a local network of food producers. It facilitates the distribution of local and seasonal products to local markets [49]. The following points can be raised regarding the social aspect: It improves access to fresh, healthy, and nutritious food [27,50]. It has a positive impact on food security. It provides food for urban residents [6,32,49,51–54]. It provides community cohesion and community engagement [55,56]. Socially excluded and discriminated groups can be engaged in farming activities [57,58]. Practicing urban agriculture enhances vegetable and fruit intake [59–61]. Gardening is a form of physical exercise. It can release stress and enhance psychological health [32,49,62,63]. It provides farming education. It can host students and provide educational activities [64]. Due to limited access to vacant land in contemporary urban centers, rooftops are utilized as grounds for sharing food production know-how [65]. Concerning the ecological aspect, urban agriculture is significant due to the following points: By increasing the percentage of green spaces in cities, the urban heat island effect can be reduced. It can be considered part of urban greening [49,66,67]. It can reduce the issues associated with stormwater runoff [68,69]. It can recycle gray water and rainwater for irrigation. It can reconnect city dwellers and the built environment with the natural environment [6,70]. It can protect biodiversity in urban areas. It can create habitats for fauna and flora [71,72].

Urban agriculture requires vacant land, which is a precious urban resource. Due to the current urban growth, which is unavoidable, there is a competing demand for vacant land. Cultivating food within dense cities by practicing conventional soil-based methods is challenged by a lack of available land [25,36,73–77]. The rooftops of buildings in dense urban areas can be considered an alternative to decreasing vacant land. Such rooftops are unutilized spaces with direct exposure to sunlight, so they can be developed for cultivating local fresh food. As cities become denser, rooftops, as valuable urban commodities, can be adapted for food cultivation [21,25–27,33,35,74–86]. In this way, unutilized rooftops can be converted into productive grounds to assist in food security development for city dwellers [74,77,84,87]. Urban rooftop agriculture can be considered a subset of urban agriculture [25,84,88]. Urban rooftop agriculture can be defined as cultivating vegetables, fruits, herbs, and edible flowers either by utilizing conventional open-air farming methods or in greenhouses as protected rooftop environments [24,76,88–90].

Currently, the application of urban rooftop farming is minimal; however, it can become a crucial part of future food production in cities [25,77]. There is an interest in proposing solutions to decouple arable land from cultivation and grow crops in and on buildings in high-density metropolitan areas [25]. Due to rapid developments in technology, materials, and skills, rooftop farming will likely become more feasible soon [26]. Current and future buildings can be designed to efficiently utilize every available surface that receives adequate light and is accessible for frequent maintenance and irrigation for cultivating food [84,91,92]. In such buildings, potential spaces for food production include rooftops, balconies, external staircases, interior spaces, backyards, front yards, windowsills, patios, and south-facing walls [91,93]. In this vision, food, architecture, design, and cultivation are integrated to grow food in large quantity in and on city buildings [25]. By utilizing the potential available spaces in and on buildings, future urban residents may actively cultivate food [30]. This research calls for re-envisioning future urban environments as grounds for cultivating food efficiently close to where a large percentage of the globe's population live [9,25,29].

1.1. Purpose of the Research

The principal purpose of this research is to suggest a series of design recommendations for architects interested in designing residential buildings capable of rooftop food production. Specific design recommendations must be considered to integrate edible plants into the built environment. Cultivating food on rooftops demands specific infrastructure [91]. The notion of food production on rooftops in residential buildings should be considered during the preliminary design phase. It is the task of the architect to address the necessary infrastructure for cultivating food during the earliest phases of architectural design. The proposed design recommendations offer essential guidance for architects during the design phase, drawing from existing urban agriculture, building-integrated agriculture, and horticulture theories. The proposed design recommendations can be implemented on residential buildings with flat roofs. By following these design recommendations, architects can create food-producing living spaces on rooftops and develop specific residential building typologies representing a synergy between agriculture and architecture. Such a residential building typology can produce food within future urban centers.

1.2. Research Questions

The following research questions are emphasized in this research: (1) Which design recommendations should architects consider regarding designing residential rooftop farms? (2) Which factors can be considered principal limitations when designing residential rooftop farms?

1.3. Research Limitations

The proposed design recommendations solely concentrate on utilizing residential building rooftops for cultivating food. Other building typologies are outside the scope of this research. Other potential spaces in and on residential buildings fall outside the scope of this research.

2. Material and Methods

A review of the literature within the disciplines of urban agriculture, building-integrated agriculture, and horticulture was conducted to collect the essential data for developing the design recommendations. The recently published literature was reviewed, and relevant data were gathered. Relevant articles, books, chapters, theses, and fact sheets were selected and reviewed.

To conduct the literature review, the subsequent keywords were searched in the Google Scholar search engine: "rooftops urban agriculture", "rooftop farming", "rooftops container garden", "vegetable gardening in containers", "rooftop vegetable garden", "green roofs food cultivation", "green roofs farming", "vertical rooftop garden", "hydroponic systems", "hydroponic systems advantages", "hydroponic systems disadvantages", "building-integrated rooftop greenhouse", and "building-integrated agriculture". The Google Books search engine was also searched, using the subsequent keywords: "cultivating food in small spaces", "growing food in small spaces", "container gardening", "raised bed(s) gardening", "rooftop gardening", and "greenhouse gardening".

The following two phases summarize the inclusion and exclusion criteria used: For phase one, the documents' titles and abstracts were screened. Manuscripts that were not written in English had not gone through the peer-review process and were not relevant to the research topic were excluded. Phase two involved reading whole texts and choosing the relevant literature to the research topic. All the selected documents had to be peer-reviewed by experts in horticulture, urban agriculture, and building-integrated agriculture and published in reputable sources. Moreover, 110 documents were chosen for evaluation after the screening and eligibility process was approved.

To extract the necessary data, full texts were read fully. Qualitative content analysis was used to assess the total collected data. Each document's content was read, and data were retrieved and summarized with notes rather than coding. The summary of each reviewed document was written manually. Each summary identified the essential concepts or components of the document. Summaries that covered the same topics were grouped, categorized, and labeled. This way, all the summarized data focused on a particular topic were categorized. To make the data coherent and concise, all of the summarized data were interlinked. The author's intention was not to change the meaning of the summarized data when making a note of, summarizing, and correlating the data. The outcome of the literature review process was a concise analysis of the reviewed documents. For the next phase, a series of design recommendations were developed based on the data extracted from the literature review. In addition, the principal limitations with regard to designing residential rooftop farms were identified, and three design proposals were presented.

3. Literature Review: Rooftop Urban Agriculture

The rooftop space in a dense urban environment can account for much of the city's surface area. The rooftop's potential is usually underutilized and unrealized [74,81,94]. Urban areas with limited open spaces, green spaces, and high land values and densities can use rooftops for intensive farming [87,95–97]. Usually, apartment building rooftops are vacant and unutilized spaces that can be utilized as farms for cultivating food [84,85,97–99]. Applying innovative materials such as efficient waterproofing membranes and lightweight growing media, along with innovative cultivation methods such as soilless systems and efficient irrigation systems, facilitates food cultivation on rooftops [95]. Vegetables, herbs, small fruit trees, and berry bushes can be cultivated on rooftops in dense urban areas [85,91,96,100]. Rooftops usually have the essential physical and climatic characteristics to support plants [94]. Rooftops usually receive sufficient sunlight [98,101]. Rooftops are free of pests such as snails and slugs [74,101]. Rooftop farms are safe from vandalism in community gardens [74]. Various fruits and vegetables can be cultivated on rooftops [102]. Leafy vegetables are the principal fresh vegetables cultivated in urban agriculture, comprising rooftop farms [26,79,82,103].

The following factors are vital and should be considered before setting up rooftop farms: (1) Climate: The globe's climatic zones can be categorized as tropical, arid, temperate, cold, and polar. Open-air farming is possible in temperate and tropical zones but limited in arid, cold, and polar zones [76,104]. By utilizing innovative cultivation methods, food can be grown in controlled environments such as greenhouses, modular production units, or indoor environments in arid, cold, and polar climates [104]. (2) Sunlight: The amount and duration of sunlight the rooftop receives are crucial factors. Most vegetables, such as tomatoes, peppers, eggplants, cucumbers, squash, peas, beans, beets, lettuce, kale, Swiss chard, carrots, and such, require a minimum of six to eight hours of direct sunlight per day [26,93,98,100,105–114]. (3) Wind: In dense urban areas, rooftop container gardens, raised beds, and green roofs under an open sky are exposed to the elements. Rooftops can be exposed to constant wind, which is usually stronger than that at ground level. Wind can damage plants by tearing off their leaves and breaking their branches. Furthermore, blossoms might be torn off before they can be pollinated. Wind can result in soil dryness and the dehydration of plants. Wind can be filtered or deflected by constructing bamboo, reed screens, trellises, walls, or tall parapets [26,79,81,92,95,98,100,101,105,107,110]. (4) Shade: rooftops near taller buildings are not ideal places for setting up rooftop farms due to neighboring buildings' cast shade [81,92,115]. (5) Water source: Proximity to a water source, such as an outdoor faucet on the rooftop, is essential [87,95,98,100,106,116]. Besides tap water, there are other irrigation sources like well water, recycled rainwater, or graywater [76,92]. To effectively water the plants, irrigation systems should be installed on rooftops [87,95,98,100,106,116]. (6) Electricity: electric sockets should be installed on the rooftop [98]. In addition to on-grid electricity, solar panels can be installed on rooftops [76]. (7) Extra load: The rooftop garden's infrastructure must be considered an extra load placed upon the roof structure. The roof structure should be able to sustain the additional load. When saturated, the growing media installed on a rooftop could weigh between 960 and 1600 kg/m^2. The farming infrastructure's load can be reduced using lightweight potting soil, containers such as plastic or fiberglass, and hydroponic systems [26,84,98,100]. (8) Access to the rooftop: Access via an elevator or staircase is essential. Any rooftop garden must have easy access via a staircase or elevator to carry equipment and maintain the garden [26,74,84,87,95,98]. A staircase or elevator might be shared with the residents, or due to privacy issues, an external staircase might be constructed [27,92]. (9) Safety: a rooftop garden should have a parapet around the edge [92,95]. (10) Limited rooftop space: Rooftops usually house vital mechanical systems and equipment, such as chiller plants, water tanks, solar water heaters, lift motor rooms, TV antennae, and pipes. Therefore, there might be insufficient room for cultivating food on rooftops [115]. (11) Building codes and legislation: The rooftop design should comply with building codes. Residential rooftop farms operating in cities might be required to obtain licenses and permits from local municipalities and undergo regular inspections. Ensuring permission for the rooftop farm might be an issue [65,81,84,87,92]. (12) Proper insulation: the roof should be properly insulated and waterproofed to avoid leaks in the roof [102]. (13) Logistics: transferring soil and other equipment might require a crane, which can be challenging [26,79]. (14) Installation and maintenance cost: Transferring the entire cultivation materials and infrastructure to the rooftop should be considered. Conventional cultivation methods require less installation cost than high-tech greenhouses [76]. (15) Social parameters: if the purpose of the rooftop farm is to host visitors, then sufficient space should be facilitated to gather a small to medium number of visitors. (16) Finishing surface: The rooftop finishing surface should be covered with tiles or a wooden deck that functions as a walkable platform. Rooftop surfaces in regions that receive extreme rain and snow should be covered with anti-slip and frost-resistant tiles. (17) Walking paths: paths free of any barriers should be designed on the rooftop. (18) Lightning protection system: a lightning protection system might need to be installed on the rooftop. (19) Grouped mechanical systems: to clear the rooftop surface for farming, exhaust vents, mechanical systems, and equipment should be grouped together and installed in one corner of the roof. (20) Managing rainwater runoff: to manage rainwater runoff effectively, the slope of the rooftop should be considered. (21) Privacy: Farming activities such as the passage of farmers, equipment, technicians, inspectors, and visitors might conflict with the residents' privacy. Residents might object to such activities [92] (Figure 1).

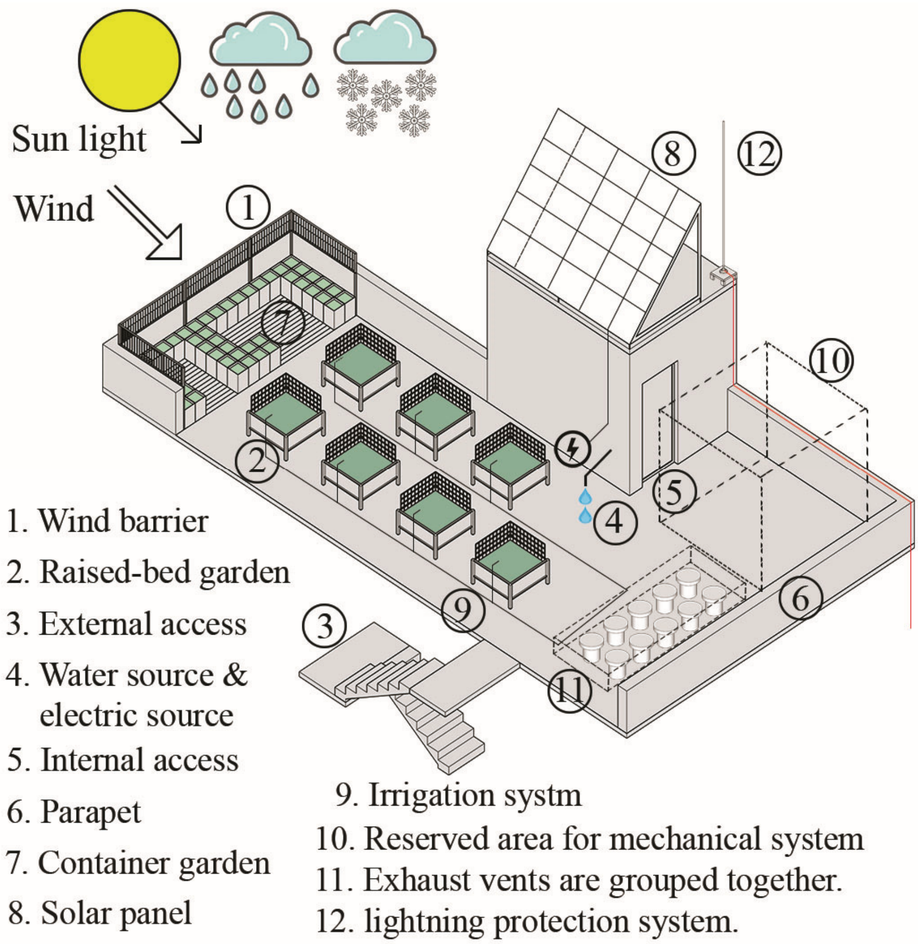

Figure 1. Various factors should be considered before designing a rooftop farm (developed by the author, 2023).

Food can be cultivated on rooftops via the following three methods: (1) open-air rooftop food production, (2) "low-tech" rooftop greenhouses, and (3) "high-tech" rooftop greenhouses. Open-air rooftop food production usually utilizes conventional soil-based cultivation methods such as rooftop container gardens, rooftop raised beds, green roofs, and vertical rooftop gardens. In this method, both horizontal and vertical surfaces on rooftops are utilized for cultivating food. Soilless systems, such as hydroponics, can also be installed on open-air rooftops (Figure 2). "Low-tech" rooftop greenhouses utilize simple cultivation methods in greenhouses without utilizing mechanized systems for controlling the indoor climate (Figure 3). "High-tech" rooftop greenhouses utilize soilless systems such as hydroponic systems in controlled environments by utilizing mechanized systems for heating, cooling, shading, and lighting (Figure 4). Open-air rooftop food cultivation, such as container gardens, raised beds, green roofs, and vertical rooftop gardens, is possible in temperate and tropical regions. Low-tech greenhouses are popular in temperate climates such as the Mediterranean region, while high-tech greenhouses can be applied to arid, cold, and polar zones [104].

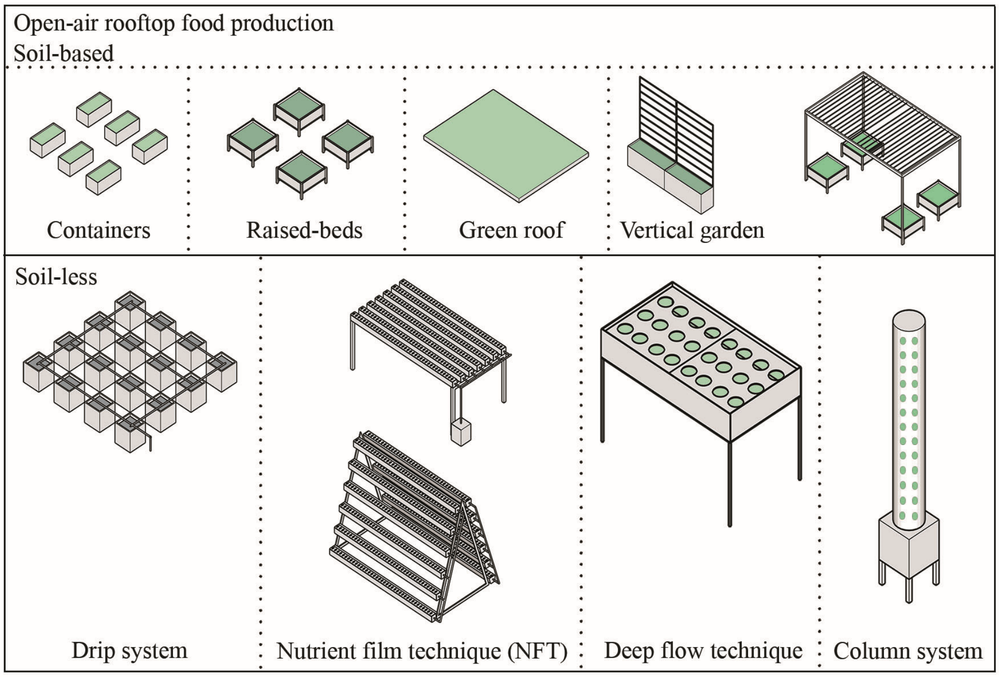

Figure 2. Soil-based and soilless cultivation methods as part of open-air rooftop food production (developed by the author, 2023).

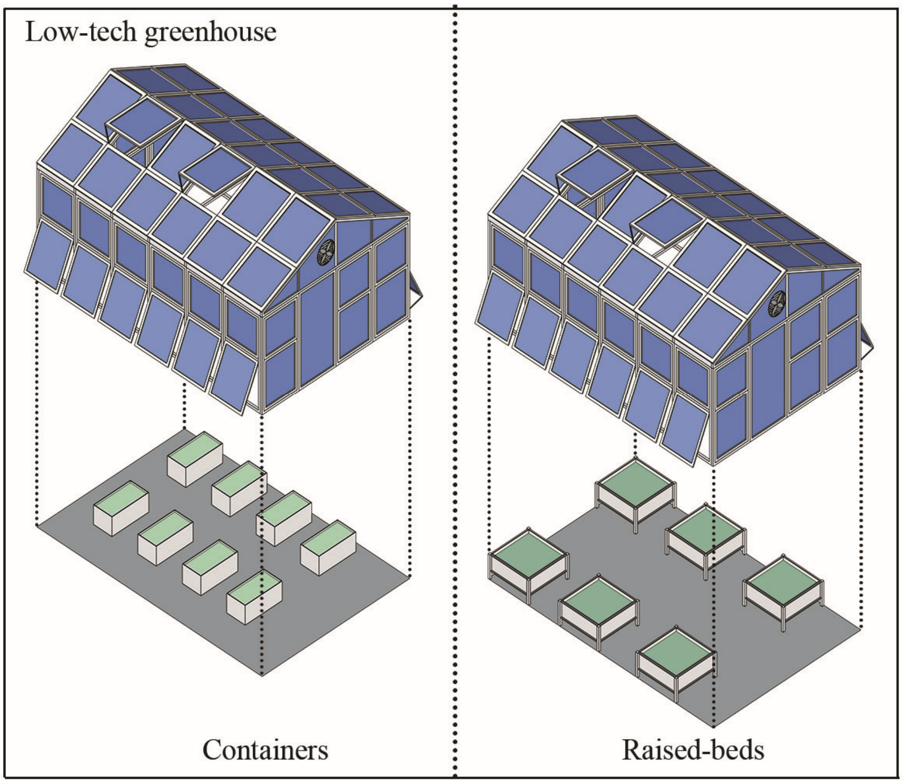

Figure 3. "Low-tech" conventional farming methods in rooftop greenhouses (developed by the author, 2023).

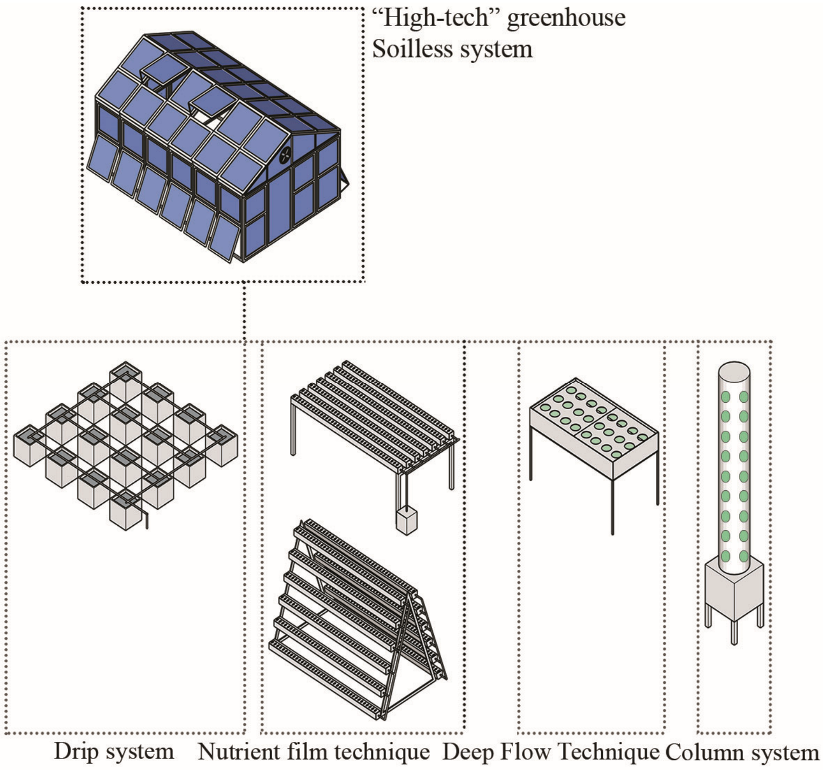

Figure 4. Various hydroponic systems can be installed in "high-tech" greenhouses (developed by the author, 2023).

3.1. Open-Air Rooftop Food Production

Urban residents consume up to 70% of the food supply, even in countries where many people reside in rural areas [117]. It is estimated that a city with an approximate population of 10 million must import 6000 tons of food each day [104,118]. It is projected that future cities heavily dependent on importing food may need to reconsider cultivating food in urban centers or the urban periphery to decrease the future burden on the agriculture sector and rural areas [104]. Open-air rooftop food production can be considered a strategy to cultivate food in existing residential buildings within the urban fabric and in future residential developments. Open-air rooftop food production currently utilizes conventional soil-based cultivation methods to enhance urban food access with minimum capital investment [76,119]. There is a growing number of residential rooftops in various developing countries in North Africa, the Middle East, and Asia that are organized to cultivate vegetables, fruits, and herbs. In such regions, usually conventional open-air rooftop food production methods such as container gardens or raised beds are applied [65].

3.1.1. Rooftop Container Garden

Vegetables, fruits, and herbs can be cultivated in containers of different sizes and shapes on rooftops [74,85,89,105,106]. Container materials can be porous or nonporous. Terracotta, clay, wood, concrete, hypertufa, fabric pots, and grow bags are porous. Glazed ceramic, plastic, resin, fiberglass, fiber stone, metal, and polystyrene foam are nonporous [98,100,101,106,108,110,114,120,121]. Wooden boxes, cans, galvanized buckets, bushel baskets, and plastic pots can be recycled and utilized as containers [98,101,107,108,110,120–122]. For rooftop gardens, metal containers should be avoided since they can overheat during the summer months and burn the plants' roots [107].

Containers should have enough depth and width to accommodate the plant's roots. They should have enough space for the extra soil required for root development [98,100,107,111–113,116,121,123]. Lettuces, radishes, beetroots, carrots, and salad leaves require a container with a minimum depth of 10 to 15 cm. Aborigines, cucumbers, peas, spinach, Swiss chard, and tomatoes need a container that is at least 20 to 25 cm deep. Beans and squash need containers with a minimum depth of 30 cm, whereas potatoes need containers with a minimum depth of 60 cm [85,95,98,123]. The mentioned vegetables are ideal for cultivating in containers [98,109,112–114,121]. Containers need regular maintenance. Potting soil, fertilizers, compost, or container manure should be regularly replaced or added [98,100,107,108,122]. Organic compost can be produced on rooftops by collecting organic waste from the residents, and by doing that, the issue of transporting commercial compost to the rooftop can be eliminated [92].

Plants in containers should receive regular water and consistent moisture [95,106,108,113,114]. The amount of water required for the containers depends on the following factors: (1) soil type; (2) climate; (3) plant exposure to sunlight and wind; (4) the plant's growth rate; (5) container size; and (6) plant type [98,121]. Water can be delivered to containers using the following methods: (1) Hand watering using cans, buckets, or pitchers [98,106]. (2) Installing drip lines: Drip lines can irrigate the container garden. Water leaks from the holes in the line at the precise spot and delivers water to the roots [95,98,105] (Figure 5).

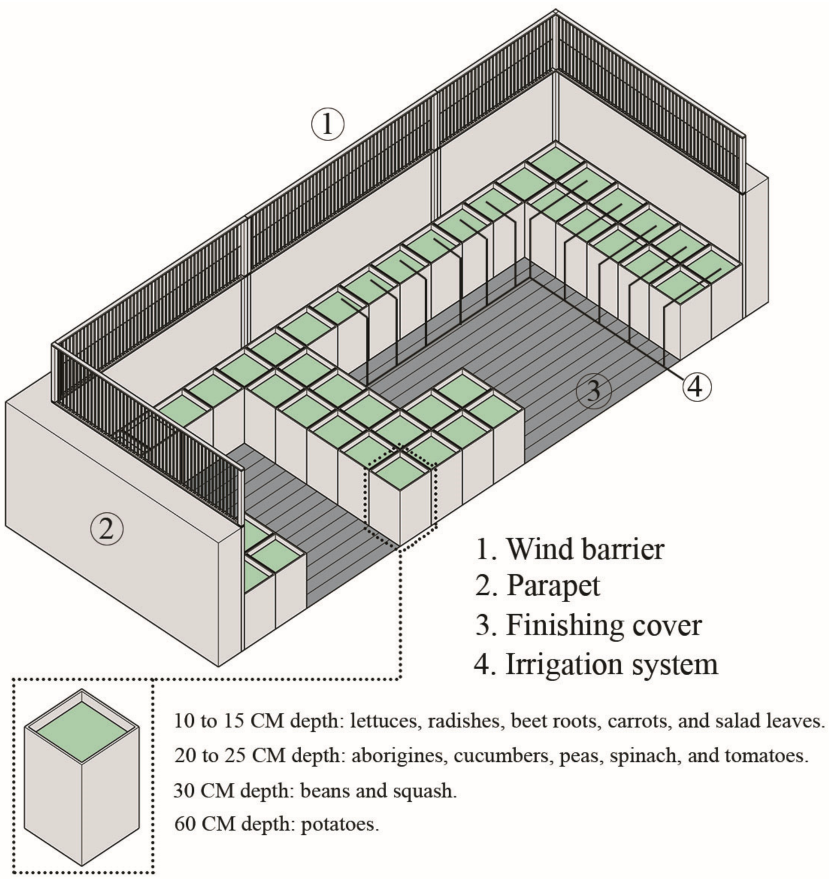

Figure 5. Rooftop container garden design (developed by the author, 2023).

Containers on rooftops require regular watering during the summer months. The climatic condition on rooftops, with its poor relative humidity and drastic daily and annual temperature fluctuations, resembles arid zones [76]. Containers are usually exposed to radiant and convective heat on rooftops; therefore, they have high rates of water loss [74,105,107,110–112,123]. It is recommended to install large containers on rooftops. Large containers are more suitable for handling harsh climatic conditions. Increased soil volume enhances the moisture-holding capacity, which means less water stress for plants [88,101,105,116]. Also, mulch placed two to five cm above the container's top will help keep it moist [74,107,114,120]. Rooftop gardening requires containers that can survive the harsh winter season. Usually, wood or plastic containers can hold soil moisture and survive the winter season [74].

Self-watering containers or sub-irrigated planters are usually more draught-resistant than normal containers. The reservoir at the bottom of the container facilitates water for plant roots [88,93,95,105,107,109]. Water is pulled from the reservoir and into the potting soil through capillary action. As the plants absorb water from the soil, more water is brought up from the reservoir to maintain ideal soil moisture levels [93,95,106,107] (Figure 6).

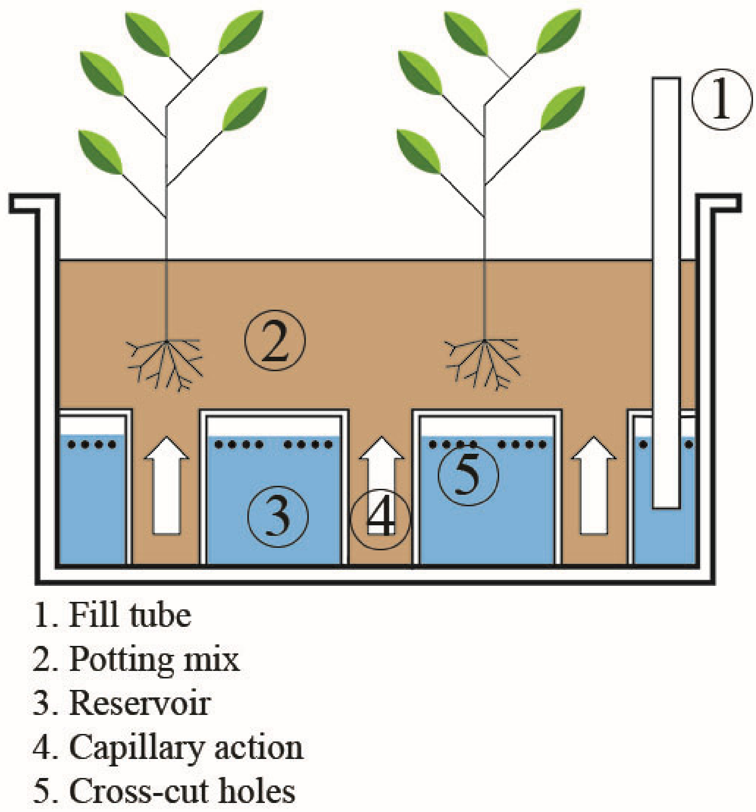

Figure 6. A cross-section of a self-watering container (developed by the author, 2023).

Containers need drainage holes so that extra irrigation water may drain out the bottom instead of soaking the soil, which could lead to root rot. Plants' roots can rot if grown in waterlogged soil. Additionally, drainage enables the flushing of extra fertilizer salts from the soil. Without drainage, the root may experience salt burn from the fertilizer [88,92,93,98,100,106–108,110–114,116,120,121].

3.1.2. Rooftop Raised Beds

A raised bed is considered an elevated gardening bed [98,100]. Compared with containers, raised beds provide more cultivation spaces [88]. It is a common method for cultivating vegetables outdoors. Raised beds can be installed on rooftops and filled with lightweight potting soil, compost, manure, and fertilizers [109]. Raised beds can be constructed from wood, steel, plastic, composites, stone, bricks, concrete, or cement blocks [88,98,100,105]. A raised bed can be placed directly on the rooftop or elevated using legs [95]. The midline of the raised bed should be easily accessible from all sides; therefore, an ideal size for gardening is a one-meter by one-meter raised bed [109] (Figure 7).

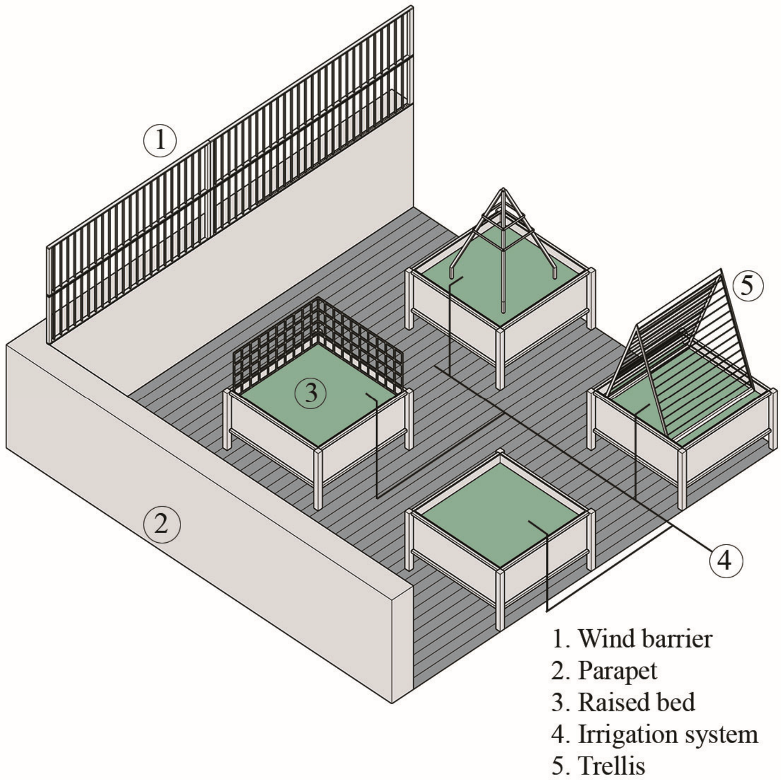

Figure 7. Rooftop raised beds with a metal cage, teepee, and hardwood stakes as vertical supports (developed by the author, 2023).

3.1.3. Green Roofs

Green roofs can be considered an alternative growing space facilitating fresh local vegetable products for city dwellers [77]. They provide an excellent opportunity to efficiently cultivate crops on rooftops that are typically unutilized [77,124]. A green roof comprises a layer of growing media utilized to fully or partially cover a building's rooftop, creating a suitable environment for growing plants [95,97,98,115,125–128]. Green roofs are also called eco-roofs or living roofs [115]. Green roofs can be productive or non-productive. They can be installed on flat or sloped roofs [129].

Usually, green roofs are categorized into two types: intensive and extensive. Intensive: This consists of a growing medium with a depth greater than 20 cm. It can support various edible plants, sedums, mosses, shrubs, and small trees. It requires regular maintenance, such as fertilizing, weeding, and watering. It is usually designed for human recreational use. It can enhance the experience of users of the rooftop. It can add ornamental value to the rooftop. Green roofs can transform underutilized spaces like rooftops into multifunctional spaces. The roof structure should support the additional dead and live loads. Extensive: This involves applying a thin layer of a growing medium (less than 20 CM) to support herbs, sedums, and mosses. It demands minimal or no irrigation. It requires low maintenance. Extensive green roofs' weight varies between 70 and 170 kg/m^2 [77,81,92,95,102,115,125–127,130–134].

Currently, innovative technologies and building products exclusively designed for green roofs facilitate the growth of rooftop farming projects [92]. Intensive and extensive green roofs can support horticultural activities and can be adapted for cultivating vegetables and herbs. Most vegetables and herbs can be cultivated on intensive green roofs due to their soil depths. The deeper the growing medium, the better it is for cultivating food. Usually, extensive green roofs can support shallow-rooted crops. Providing high nutrients and irrigation is mandatory to cultivate food on shallow extensive green roofs [33,77,92,128].

Intensive and extensive green roofs usually consist of five layers: (1) The base layer, or protection layer, is located directly above the roof structure. Its purpose is to stop water from getting into the roof's structure. (2) Drainage: This includes a waterproof membrane and root barriers. It permits additional moisture to flow out of the roof and into the downspouts. (3) A root-permeable filter layer is utilized to stop the growing medium from washing away. (4) Growing medium or soil layer: Lightweight soil usually contains nutrients, holds moisture, and facilitates the plant roots' growth. Most vegetables, herbs, and flowers require a minimum of 15 cm of growing medium. (5) The planting: it is recommended to cultivate low-growing shallow-rooted plants [33,77,98,126–128,133,134] (Figure 8).

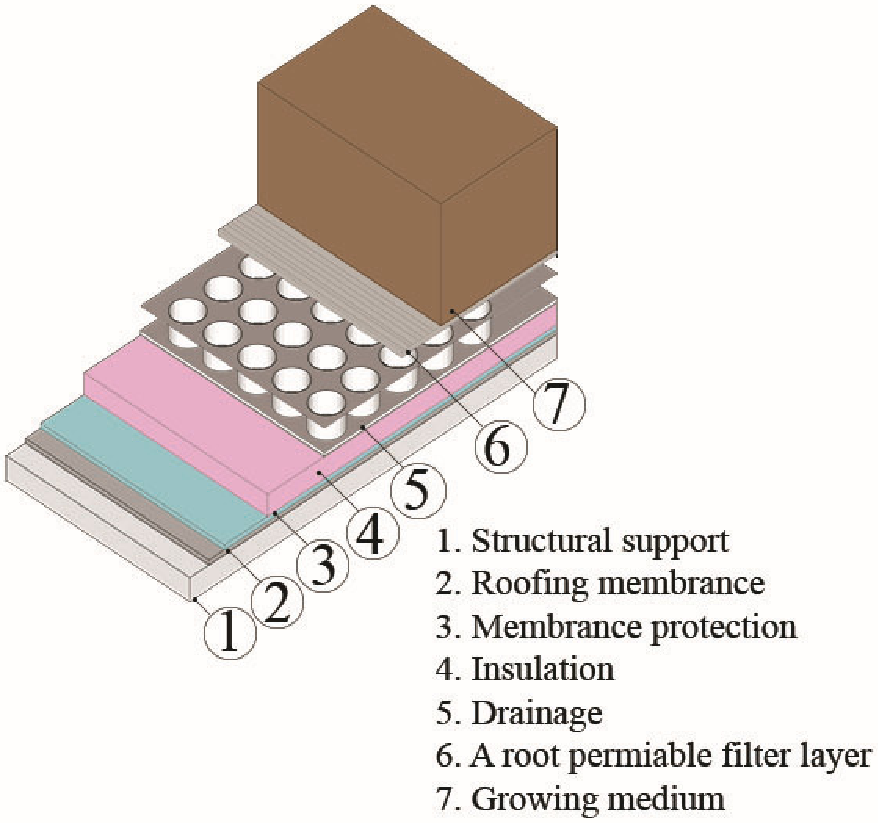

Figure 8. An example of the layers of a green roof. The arrangement of the layers is based on a review of current literature [33,77,98,126–128,133,134].

The following issues should be considered before installing green roofs: (1) It is crucial to consider the green roof's weight when designing a new building's structure [81,95]. Agricultural green roofs often have deep-growth media, usually categorized as intensive green roofs. An intensive green roof, with a substrate depth ranging from 400 to 1500 mm, can weigh between 350 and 450 kg/m^2 [115]. In addition to the mentioned load, conventional flat roofs should be designed to withstand a snow load of 100 kg/m^2. (2) Conventional flat roofs usually cost two to six times less than green roofs [81,128]. Maintenance costs should also be considered. Green roofs are typically more expensive than conventional open-air rooftop farming methods, such as container gardens, raised beds, or vertical gardens [92]. (3) Discharged water can be contaminated by fertilizers and compost, polluting the environment. (4) Clean irrigation should be accessible. (5) Inadequate access to professional labor might be a challenge. (6) Food cultivated in open-air farming, such as on green roofs, can be contaminated by the urban atmosphere [128]. (7) Maintaining a farm on a rooftop several stories above the ground is challenging. All the necessary equipment should be transferred to the rooftop. Also, cultivating crops requires considerable monitoring throughout the growing season. (8) Wind exposure can destroy vegetable crops; therefore, windbreaks should be installed to minimize the possible damage [77].

Green roof benefits can be categorized as follows: (1) Green roofs increase the thermal insulation of the roof, therefore reducing the building's winter heating and summer cooling costs. They can improve the energy efficiency of the building [92,102,126,133,135–139]. (2) The local biodiversity can be conserved by planting a high diversity of plant species on green roofs. High-diversity plant species can attract varied species. Green roofs, compared to non-green roofs, can attract more birds, arthropods, and gastropods [130,140–147]. (3) Green roofs can restore lost green spaces due to large-scale developments in dense urban areas. By installing green roofs, additional vegetated surfaces can be added to cities [87,129,134,148,149]. (4) Green roofs can catch and absorb rainwater and slowly release it to the drainage system; therefore, the intensity and quantity of stormwater runoff can be lessened. Depending on the type of green roof, approximately 40% to 100% of stormwater runoff can be reduced [77,102,127,150–152]. (5) Green roofs can contribute to limiting the urban heat island effect. They reduce the air temperature on the rooftop through shade and increase evapotranspiration. Green roof temperatures can be between 1 °C and 4 °C lower than conventional roofs [115,127,132,153–159]. (6) By installing green roofs, urban air quality can improve. Green roofs can reduce particulate matter such as PM_{10}, $PM_{2.5}$, O_3, nitrogen dioxide, and sulfur dioxide in ambient air [68,133,160–163].

3.1.4. Vertical Rooftop Garden

Every building has external walls or vertical surfaces exposed to sunlight, thus offering the potential to cultivate crops [95]. The cultivation area can be increased by utilizing the available vertical surfaces for growing food [105,107,110]. In dense urban areas, more vertical surfaces might be available that receive natural light than horizontal surfaces [93,95,98,100,164]. Therefore, vertical greening has a greater chance of development than horizontal ground-level green development [94,165].

Modular units and wall planters are prefabricated systems designed to be affixed to walls, allowing edible plants to receive abundant sunlight. Modular units can be mounted on south-facing walls on rooftops, which allows the plants to grow vertically. The modular units consist of shallow pockets filled with light-growing media [105]. Walls of any size and shape can be covered by modular units that can be interconnected and fixed together [123]. Wall planters are specially designed for wall mounting, utilizing brackets and hooks. Typically, they are made of plastic, metal, or fabric [107] (Figure 9). Alongside prefabricated systems, trellises can also be attached to south-facing walls. At the same time, containers are placed in front of them, allowing twining and vining crops to grow upwards using the trellises [98,101,106,110]. A shelf can be installed against a south-facing wall, and containers can be arranged on its shelves [123] (Figure 10). Parapets can be made from metal grid panels and used for climbing plants [92].

By installing three-dimensional trellises on rooftops, plants and vines can be supported. Trellises can either be freestanding or fixed to posts securely attached to the roofs or existing walls [95,98,105] (Figure 11). Trellises can support cane berries like raspberries or blackberries and vine fruits like grapes and kiwis [93,98]. A trellis consists of horizontal wires that can handle the weight of heavy fruit vines [93]. Trellises can be made from lumber, metal, or bamboo [98,107,123].

Some vegetables that produce large fruits, such as eggplants, tomatoes, squash, melons, and peppers, can be trained upwards. The mentioned plants can be secured to a hardwood stake, teepee, metal cage, or trellis for proper support. Twining crops, such as beans and pole beans, as well as vining crops, like cucumbers, winter squash, pumpkins, peas, and melons, can grow upward by wrapping around hardwood stakes, teepee legs, bamboo poles, and similar supports [93,95,98,100,106,123,164]. Hardwood stakes, teepees, metal cages, and bamboo poles can support the mentioned crops and create a living wall of vegetation in containers, raised beds, and green roofs [123] (Figure 12).

Growing vegetables vertically has advantages: (1) it allows plants to be exposed to lighted space [93,95,98,123]; (2) more vegetables per square meter can be planted; (3) vegetables grown vertically benefit from strong air circulation, which keeps leaves dry and reduces the risk of fungus [95,105,123]; (4) it stops illness from spreading by preventing soil from washing onto leaves; and (5) vegetables are easy to monitor and harvest [95,105].

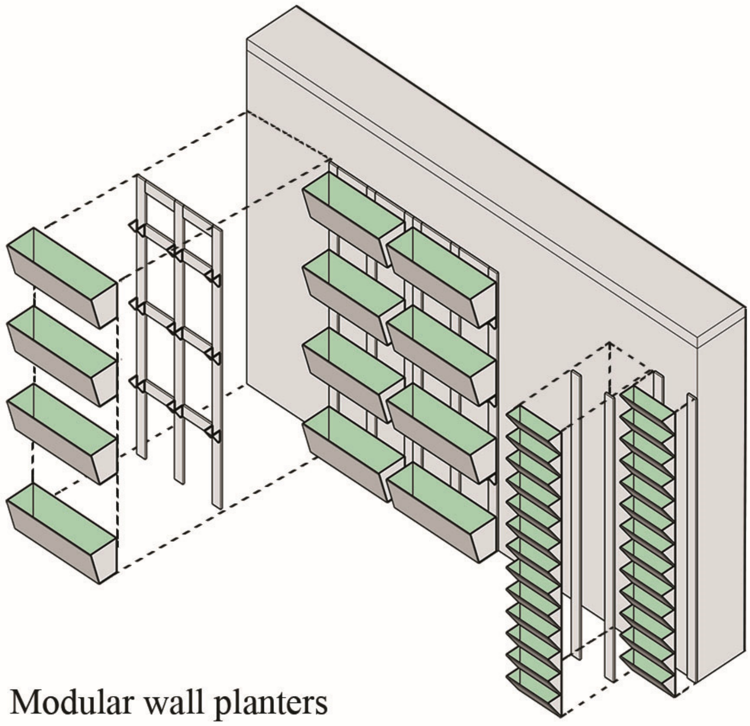

Figure 9. Modular wall planters attached to a south-facing exterior wall (developed by the author, 2023).

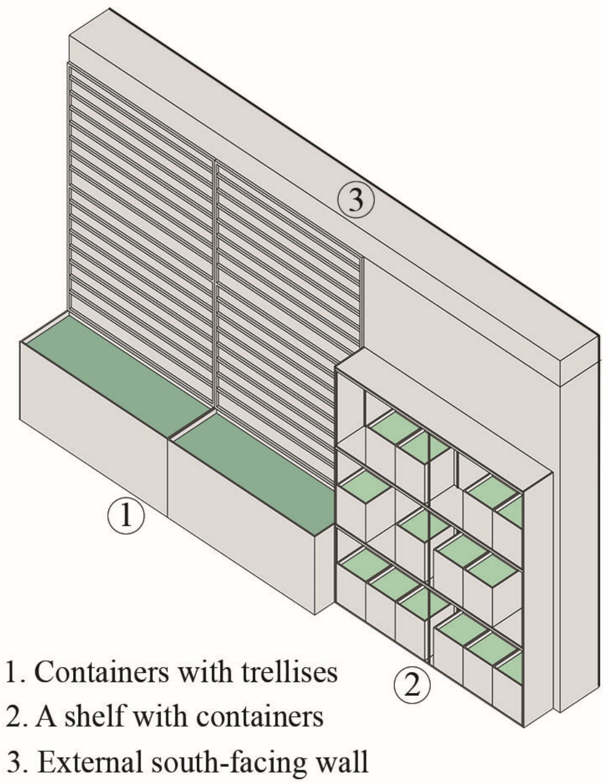

Figure 10. Containers with a vertical support and a shelf with containers (developed by the author, 2023).

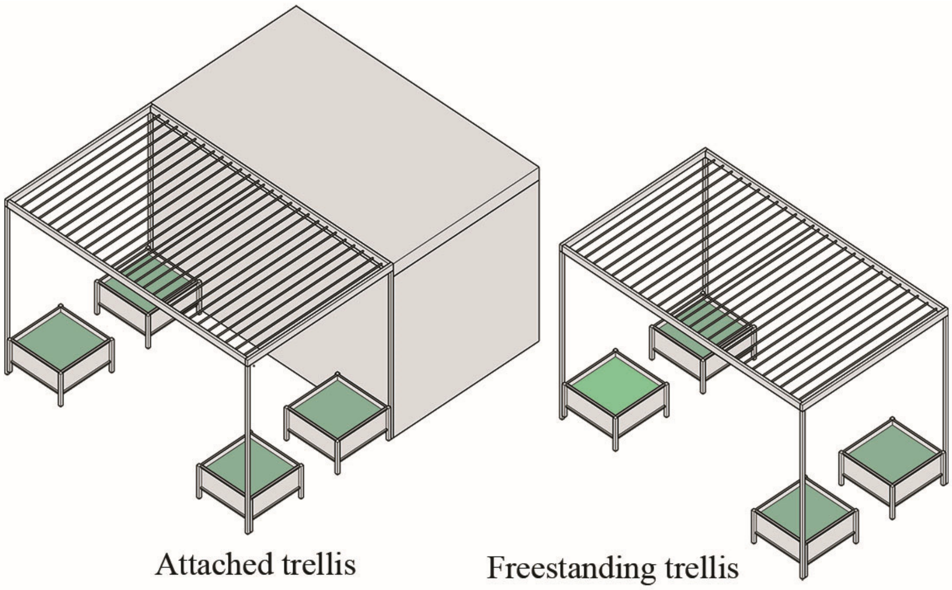

Figure 11. Attached trellis and freestanding trellis (developed by the author, 2023).

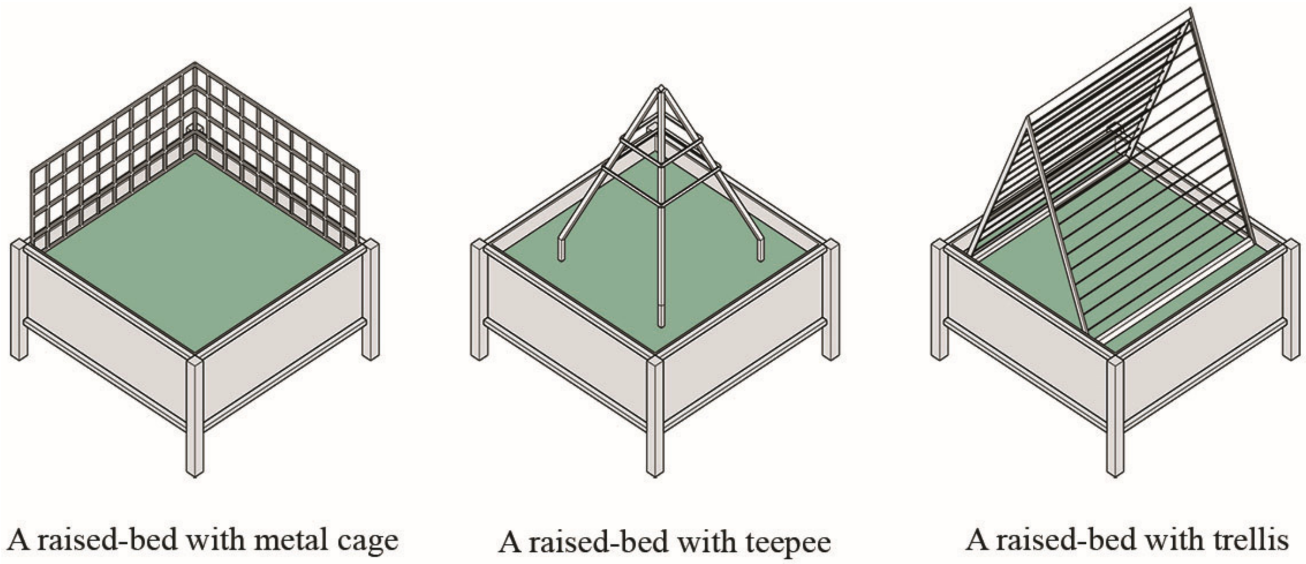

Figure 12. Raised beds with vertical supports (developed by the author, 2023).

3.2. "Low-Tech" Rooftop Greenhouses

Cultivating food in greenhouses on rooftops is another approach to urban agriculture. Greenhouses are often installed on rooftops in dense urban areas due to a lack of land and land costs. Cultivating greenhouses requires exposure to natural light, which is difficult to get at ground level, which makes rooftops an ideal location for installing greenhouses [26,79]. Rooftop greenhouses can be implemented on buildings such as residential blocks within dense urban centers [50,166]. Rooftop greenhouses consist of a greenhouse constructed on the roof of a building [25]. Vegetables, fruits, and aromatic plants are usually cultivated in greenhouses either by following conventional farming techniques or in soilless culture systems like hydroponic systems [166,167].

A greenhouse is a structure that houses crops and shelters them from the elements [168,169]. It is built from a frame covered by transparent glazing. It uses sunlight to create a favorable environment for crops to grow. It is possible to extend the growing seasons in greenhouses [168]. "Low-tech" rooftop greenhouses are conventional greenhouses that do not require climate control systems. Various crops can be cultivated in such unconditioned greenhouses all year around in moderate climates [33,170]. Rooftop greenhouse structures can be categorized into the following: (1) cold frame, (2) attached greenhouse, and (3) A-frame greenhouse. (1) Cold frame: this is used in spring and fall to extend the growing seasons (Figure 13). (2) Attached greenhouse: This is a lean-to structure attached to a south-facing wall. Attached greenhouses are usually made with glass windows. The construction cost is usually lower than for freestanding greenhouses [168]. (3) A-frame greenhouse: A detached structure that stands apart on the rooftop. It is usually made with glass windows [100,168,171] (Figure 14).

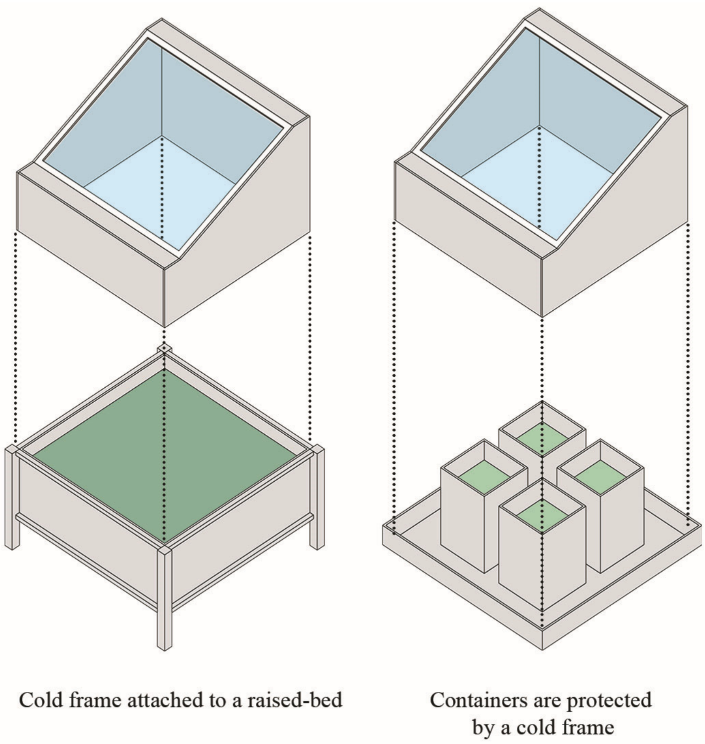

Figure 13. Cold frames can extend the growing season (developed by the author, 2023).

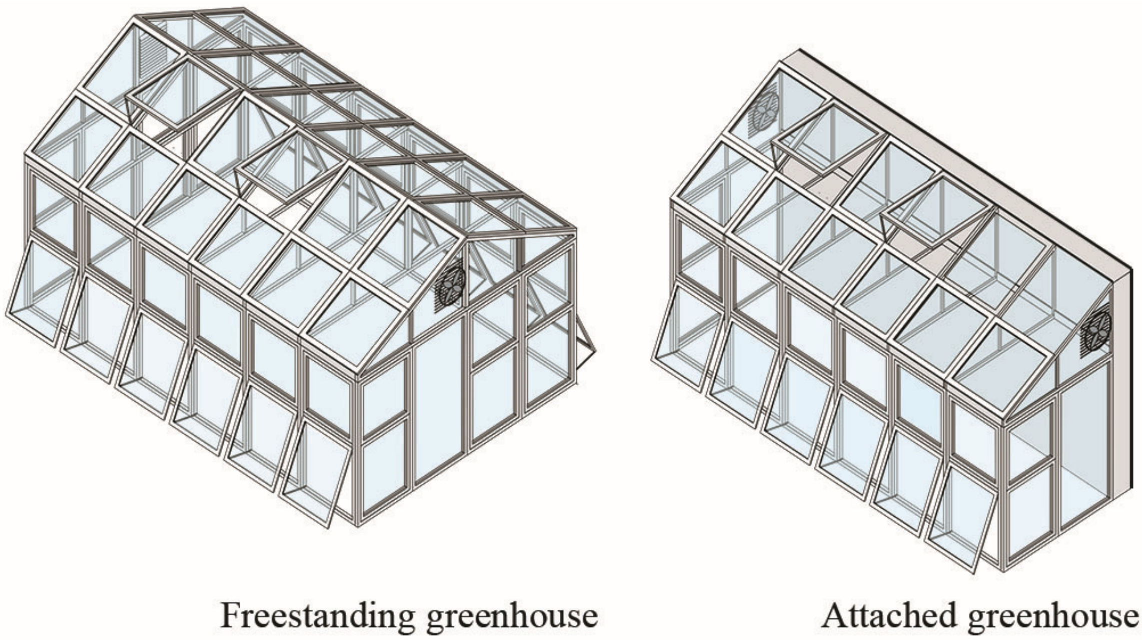

Figure 14. Attached greenhouse and freestanding greenhouse (developed by the author, 2023).

Greenhouse structures can be made from galvanized steel, aluminum, plastic, wood, and PVC [35,168,171]. Urban rooftop greenhouses are often exposed to strong winds; as a result, they should be constructed as stable structures with strong cover materials that can withstand wind forces [33,88,168,171]. A greenhouse structure should be sheltered from the wind by setting up barriers. Exposure to wind can contribute to greenhouse heat loss [171,172]. Galvanized steel is an ideal structural choice. It can withstand strong winds and snow loads [168]. Glazing is an essential element of any greenhouse. It facilitates the entry of sunlight into the greenhouse. It is attached to the frame and is the most expensive component of the greenhouse [173]. It can be made from glass panels, plastic sheeting, polyethylene films, acrylic sheets, translucent fiberglass, polyvinyl chloride (PVC), copolymers, and polycarbonate panels or rolls [7,168,171–173].

The following points should be considered when designing a rooftop greenhouse: (1) Orientation to the sun: the east-to-west orientation is preferable to the north-to-south orientation. (2) Climate: low-tech rooftop greenhouses can be installed in temperate and tropical regions. (3) Shadow: neighboring buildings or mechanical systems might cast shadows on the greenhouse. (4) Building codes: The rooftop greenhouse structure and cover should comply with the local building codes. Selected materials should comply with fire safety laws (avoid inflammable materials) and load-bearing laws (snow and wind loads). Fire safety laws and load-bearing laws should be considered when designing open-air rooftop food production, "low-tech" rooftop greenhouses, or "high-tech" rooftop greenhouses. (5) Hosting building equipment: due to a lack of available space on the rooftop, the building's mechanical system might be installed inside the greenhouse. (6) Light condition inside the greenhouse: The selected greenhouse cover should allow maximum natural light transmission. Attention to proper lighting conditions inside the greenhouse is essential since crops' growth depends on it. (7) Natural ventilation: installing side and roof vents is crucial for facilitating indoor air movement [169].

3.3. "High-Tech" Rooftop Greenhouses

As the globe experiences rapid urbanization, cultivating food in "high-tech" rooftop greenhouses can be regarded as an alternative secondary source to conventional soil-based farming [29]. They can address the growing concerns regarding urbanization and food security [50,104,174]. In dense urban areas where vacant land suitable for cultivation is limited, utilizing innovative high-tech technologies that require minimum cultivation space offers tremendous opportunities for space-confined cultivation [25]. Situating farming systems such as "high-tech" greenhouses in line with soilless cultivation systems on and in buildings can be considered building-integrated agriculture (BIA) [30,35,175].

"High-tech" greenhouses can supply a significant quantity of fruits, vegetables, herbs, and medicinal plants [50]. "High-tech" rooftop greenhouses can be considered a form of controlled-environment agriculture (CEA) in cities. CEA focuses on applying innovative, high-tech cultivation methods in controlled environments in and on buildings. In "high-tech" rooftop greenhouses as controlled environments, high-performance soilless cultivation methods such as hydroponic systems, grow lights, and climate control systems that are operated by computers are installed. In this method, high-quality vegetables and fruits can be cultivated on a large scale all year round. Crop yields can be increased, while production costs can be reduced [7,33,76]. Controlled-environment agriculture aims to maintain the growing conditions to optimize crop cultivation [36,176] (Figure 15). If the purpose of the greenhouse is to produce vegetables, fruits, and herbs all year round, then it should be equipped with the following systems: (1) heating, (2) cooling (ventilation), (3) shading devices, and (4) lighting devices.

(1) Heating: the purpose of heating is to stabilize the greenhouse temperature. Propane heaters, electric fan heaters, gas or oil heaters, solar heaters, and radiant heat lamps are heating options to warm the greenhouse [168,173]. (2) Cooling (ventilation): To avoid overheating, a proper ventilation system is necessary. Airflow can be provided through doors, side vents, and roof vents. Vents can be either hand-operated or automatically operated by connecting them to a thermostat. In "low-tech" greenhouses, vents are usually operated manually, while in "high-tech" greenhouses, vents are operated automatically.

Exhaust fans are usually installed on greenhouse roofs to draw the hot air outside. Exhaust fans are more effective than vents since they provide more indoor airflow. Portable oscillating fans can also facilitate internal air movement. Fogging and pad-and-fan systems can effectively lower the air temperature in greenhouses [7,26,104,168,171–173]. (3) Shading devices: Providing shade is essential to decrease the solar radiation load reaching the plants. It protects the plants from overheating and burning during the summer months. Shade can be provided by installing external blinds, internal blinds, and a shade cloth. Shading devices can operate manually or automatically [168,171]. (4) Lighting devices: As mentioned before, plants require a minimum of six to eight hours of sunlight daily. Supplementary lighting might be required during autumn, winter, or extended periods of sunless days [9,168,171]. In high-tech greenhouses, incandescent/halogen lamps, fluorescent light tubes, metal halides, high-pressure sodium lamps, and light-emitting diodes (LED) are highly utilized [7]. Light-emitting diode (LED) grow lights can be installed in greenhouses with a life expectancy of eight to ten years. LED grow lights are specifically manufactured for cultivating crops in controlled indoor environments to enhance crop yields and reduce production costs. The advantages of LED grow lights are their compact design, light quality, low thermal energy generation, low energy cost, and durability [7,30,76,168,171]. Automatic systems are installed to control the greenhouse microclimate via controlling heating, cooling, shading, and lighting devices [9].

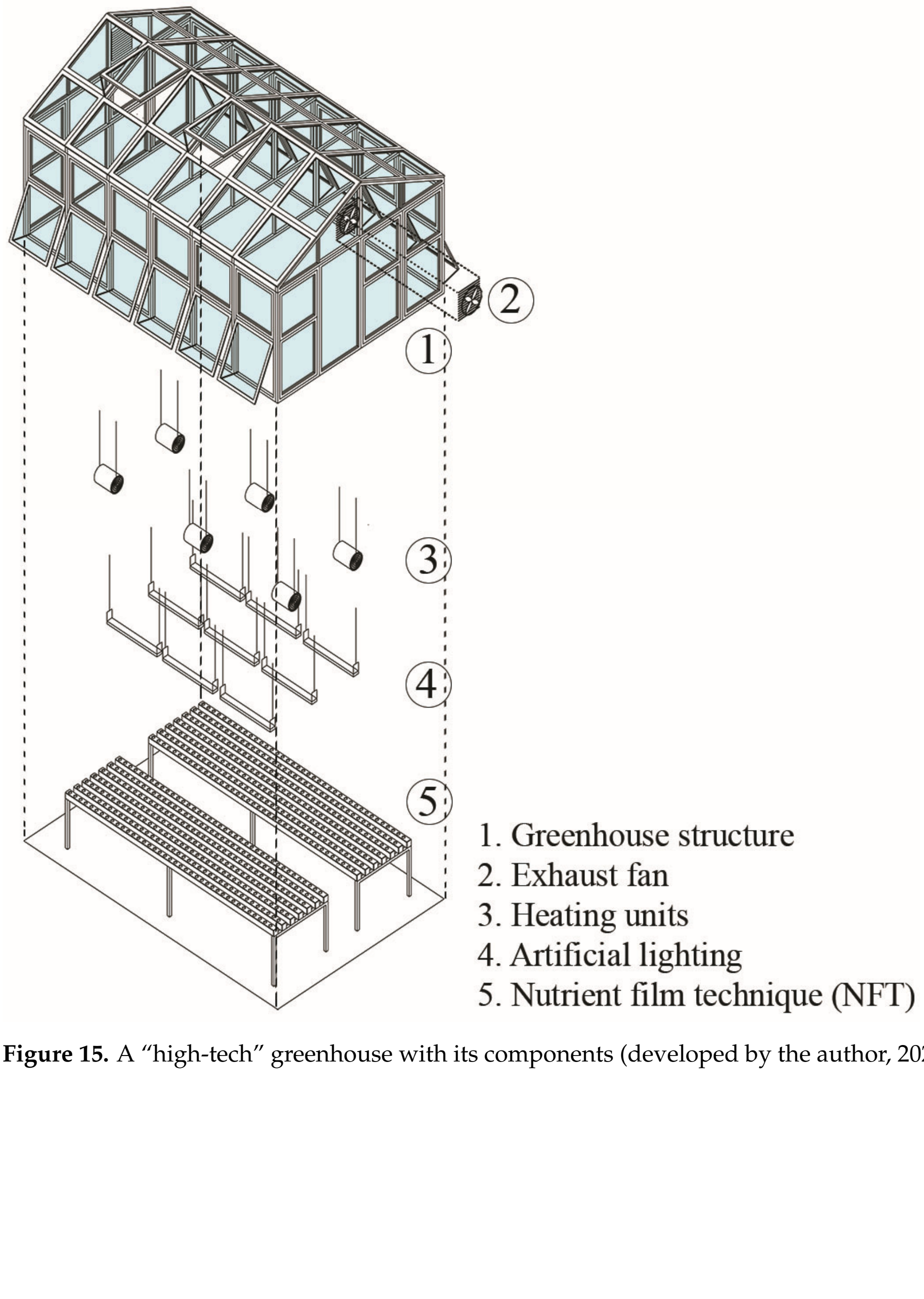

Figure 15. A “high-tech” greenhouse with its components (developed by the author, 2023).

3.3.1. Soilless Cultivation Methods in "High-Tech" Rooftop Greenhouses

Farming without soil can be considered an innovative method for cultivating food. It includes hydroponics, aeroponics, and aquaponics [177]. Various fruits, vegetables, herbs, pharmaceutical plants, sprouts, and microgreens can grow in hydroponic systems in rooftop greenhouses [25,85,177–179]. By utilizing hydroponic systems, the crop yield is maximized compared to conventional soil-based methods [82,85].

Hydroponic systems equipped with grow lights can be installed in regions that do not receive sufficient sunlight [177]. In this system, crops can be cultivated in deserts and infertile lands, such as mountainous regions [179–181]. Hydroponics is a suitable cultivation method in congested urban centers where there is a shortage of vacant land for cultivating food [177,181–184].

Plants in hydroponic systems are grown without soil. The plant's roots are submerged in a nutrient-rich solution [177–181,183–187]. The amount of nutrient solution is calculated; therefore, the amount necessary for the plant's growth is delivered to the roots [181,183,186]. Plant roots can be supported and maintained in hydroponic systems by peat, moss, perlite, rock wool, vermiculite, sand, gravel, or soil pellets. Hydroponic systems can be categorized into the following types: (1) the wick system; (2) the drip system; (3) the ebb and flow or flood and drain system; (4) the nutrient film technique (NFT); (5) deep flow technique (DFT) pipe system; (6) the floating raft system; and (7) the column system [177,178,180,184,185]. The mentioned systems equipped with grow lights can be assembled on rooftops in greenhouses to cultivate crops intensely. Drip systems, the nutrient film technique (NFT), deep flow technique (DFT) pipe systems, and column systems are well-known hydroponic systems used on residential rooftops [85].

In a drip system, water and nutrient solutions can be delivered to plants using little hoses and drip emitters [177,180,185,188]. This system pumps water and nutrient solutions directly from the tank to each plant's root area in the right proportion [177,184,188,189]. Typically, plants are cultivated in a growing medium so the nutrient solution and water drip down gradually [177,180]. Water and nutrient solutions can be recycled or drained in this system [180,185].

In the nutrient film technique (NFT) system, water and the nutrient solution are continually pumped from the reservoir to the channels known as gullies [177,180,184–186,188]. Plants are arranged in the net cups and placed in channels, and their roots are suspended in passing water and nutrient solutions [177,178,180,183,186,188]. The roots of the plants must be constantly kept moist. The plant roots are always in direct contact with water and nutrient solutions; therefore, the roots are more susceptible to fungal infection. In this system, water and nutrient solutions can be recycled several times. The NFT system is totally dependent on a water pump to deliver water and nutrient solutions to the plant's roots [177,180,183].

In a deep flow technique (DFT) pipe system, water, and nutrient solutions are pumped through PVC pipes. Plastic net pots are put in the holes drilled in the PVC pipes. All the plants are put into plastic net pots. The plant's roots touch the shallow nutrient solution and water stream in the PVC pipes. This system's pipes can be organized horizontally or vertically on several levels. Water and nutrient solutions are transferred from one channel to the next via drip lines. This system is suitable for cultivating low-growing crops in multiple zig-zag vertical plains in interior spaces [178,180].

In the column system, crops are cultivated in light growing media supported by the column. The column should be able to support the weight of the pots, growing media, plants, and irrigation system. Using a column system makes intensive crop cultivation per unit area possible. One column can be installed in each square meter. On a rooftop of 100 m^2, it is possible to install 100 columns approximately. The height of each column is 1.7 m, and each column hosts 32 plants [85].

The advantages of cultivating plants in hydroponic systems in comparison to conventional soil-based agriculture are as follows: (1) No soil is required [180,185]. (2) Compared to conventional farming, plants grow more quickly and have smaller roots because the nutrients are sent straight to the roots [177,179,185]. Intense cultivation in small areas in any location is possible since plants can be grown closer to each other [177,179,180,185]. (3) Hydroponic systems enable increased productivity per acre, high-density cultivation, higher quality harvests, and effective nutrient, water, and aeration controls [76,85,177–181,186]. Hydroponically produced plants are fed a balanced diet, making them healthier than their soil-grown counterparts [183,186]. (4) Hydroponic crops can be grown all year and are called off-season because weather changes do not affect them. Harvesting locally multiple times per year without utilizing the existing arable land is possible [85,177,181,183,185–187]. (5) Labor can be minimized in hydroponic systems [85,118,177,178,181,183,184,186]. Various conventional soil-based agriculture procedures such as weeding, spraying, watering, and plowing are eliminated [177,181]. (6) Water consumption is reduced in hydroponic systems. Water and nutrient solutions can be partially or entirely recycled [35,85,118,177,178,180,181,183,185–187]. (7) Compared to traditional farming, larger yields can be achieved since more plants per unit can be cultivated [26,85,92,177,183,184].

The principal disadvantages of soilless farming can be categorized as follows: (1) Hydroponic systems require technical knowledge and operational skill [177,179,181,183,184,187]. Constant monitoring of the system is necessary. (2) The high upfront cost of purchasing and assembling the system might burden the user [85,177,179,183,184,187]. (3) In hydroponic systems, water-borne diseases can spread from one crop to the next since the plants share identical nutrients [177,181,183,184,187]. (4) Oxygen shortages can hinder production, which might cause crop failure [177]. (5) The EC, pH, and optimal nutrient solution concentration level should be constantly monitored [177,180]. (6) To keep the system operating, lighting and energy supply are essential [177,179,181,187,188]. As an example, the amount of energy consumed to cultivate one kilogram of lettuce by utilizing hydroponic systems in a greenhouse in Arizona, USA, is approximately 82 times more than cultivating one kilogram of lettuce using traditional methods of cultivation in the same region [190].

3.3.2. "High-Tech" Rooftop Greenhouses: Benefits and Challenges

The benefits of installing "high-tech" greenhouses on rooftops can be considered as follows: (1) In comparison with conventional soil-based agriculture, higher yields are possible [26]. "High-tech" greenhouses facilitate the cultivation of high-quality nutritious food throughout the year within urban areas [26,29,36,90,104,191]. (2) Rooftop farming promotes local food production [7,25,30,166,167]. (3) "High-tech" greenhouses can expand growing food in climates and locations unsuitable for cultivation [26,29,104,192]. (4) They can assist city dwellers to reconnect with food cultivation in urban centers [25]. (5) They improve the roof's insulation; therefore, the energy requirement for cooling and heating the building is reduced. They can optimize the energy efficiency of the building [7,25,166]. (6) The internal environment of rooftop greenhouses is precisely controlled; therefore, the consumption of urban resources such as water and electricity is minimized [29,36]. (7) It is projected that future rooftop greenhouses will link their heat, water, waste, and CO_2 to the metabolism of buildings to optimize resource use [7,25,166]. (8) Graywater and rainwater can be recycled for irrigation [7,25]. (9) They provide precise lighting conditions, humidity, and temperature that lead to high yields [193]. (10) Compared to conventional farming, less water for irrigation is needed [181,183,187]. (11) Food can be cultivated in the minimum available space [29,36,194]. (12) Rooftops, as unused or underutilized spaces, can be converted into productive grounds [26].

The principal challenges of installing "high-tech" greenhouses on rooftops can be summarized as follows: (1) The initial cost of establishing, equipping, and implementing a "high-tech" greenhouse is usually higher than conventional "low-tech" greenhouses. (2) The energy consumption is higher than conventional open-field agriculture. As an example, in order to cultivate one kilogram of tomato in a "high-tech" greenhouse situated in Washington State (WA), approximately 231 times more energy is required than cultivating the same amount of tomato in open-field farming in the same state [195]. (3) The variety and quantity of vegetables and fruits that can be cultivated are lower than in conventional open-air farming. (4) Labor that is specialized to maintain a "high-tech" greenhouse has to be trained. (5) The high labor cost, especially in the developed world, can be challenging. (6) Local zoning laws can be a principal challenge, preventing the installation of greenhouses on rooftops [7,21,25,26,30,76,92,196,197].

4. Developing Architectural Design Recommendations

In this section, the design recommendations that have been extracted from the literature review will be reviewed. The proposed design recommendations can be categorized into (1) preliminary design recommendations and (2) selecting the appropriate farming methods.

Regarding the preliminary design recommendations, the following factors should be considered before designing a rooftop farm: (1) Climate: Open-air rooftop farming is possible in temperate and tropical zones. Rooftop farming in arid, cold, and polar zones can be done in "high-tech" greenhouses. (2) Sunlight: the rooftop should receive a minimum of six to eight hours of direct sunlight daily. (3) Wind: Open-air farming can be exposed to constant wind. Major wind directions should be identified, and barriers such as screens, parapets, and trellises should be designed. (4) Shade: rooftop farms should not be designed near tall buildings due to the neighboring building's cast shade. (5) Water source: An outdoor faucet and irrigation system should be considered on the rooftop. Recycling rainwater and greywater can be considered. (6) Electricity: Electric sockets should be installed on the rooftop. Solar panels can be considered if sufficient space is available on the rooftop. (7) Extra load: The rooftop garden's infrastructure must be considered an extra load placed upon the roof structure. The roof structure should be able to sustain the additional load. When saturated, the growing media installed on a rooftop could weigh between 960 and 1600 kg/m^2. The farming infrastructure's load can be reduced using lightweight potting soil, containers such as plastic or fiberglass, and hydroponic systems [26,84,98,100]. (8) Access to the rooftop: Access via an elevator or staircase is essential. Due to the privacy issue, an external staircase might be designed. (9) Safety: parapets should be designed around the rooftop edge. (10) Limited rooftop space: sufficient space should be allocated for installing mechanical systems and other essential equipment; therefore, there might be insufficient space for designing rooftop gardens. (11) Building codes and legislation: local building codes must be checked. (12) Proper insulation: the roof should be properly insulated and waterproofed. (13) Logistics: transferring soil and other equipment might require a crane, which can be challenging [26,79]. (14) Installation and maintenance cost: transferring, installing, and maintaining the rooftop farm should be considered. (15) Social parameters: if the purpose of the rooftop farm is to host visitors, then sufficient space should be facilitated to gather a small to medium number of visitors. (16) Finishing surface: The rooftop finishing surface should be covered with tiles or a wooden deck that functions as a walkable platform. Rooftop surfaces in regions that receive extreme rain and snow should be covered with anti-slip and frost-resistant tiles. (17) Walking paths: paths free of any barriers should be designed on the rooftop. (18) Lightning protection system: a lightning protection system might need to be installed on the rooftop. (19) Grouped mechanical systems: to clear the rooftop surface for farming, exhaust vents, mechanical systems, and equipment should be grouped together and installed in one corner of the roof. (20) Managing rainwater runoff: To effectively remove rainwater, consider a minimum roof slope ratio of 1:50. This ratio is suitable for rooftops in regions with minimal rainfall or snowfall. For regions that receive heavy precipitation, a slope ratio of 1:20 is recommended [198]. (21) Privacy: Farming activities such as the passage of farmers, equipment, technicians, inspectors, and visitors might conflict with the residents' privacy. Residents might object to such activities (Table 1).

Table 1. Proposed preliminary design recommendations.

Preliminary Design Recommendations	
Climate	Temperate and tropical: consider open-air rooftop farming. Consider a "low-tech" greenhouse.
	Arid, cold, and polar zones: consider a "high-tech" greenhouse.
Sunlight	Minimum of six to eight hours of direct exposure to sunlight is essential.
Wind	1. Identify major wind directions. 2. Design wind barriers.
Shade	Consider the neighboring building's cast shade.
Water source	Consider outdoor faucets and irrigation systems.
Electricity	1. Consider electric sockets on the rooftop. 2. Consider solar panels on the rooftop.
Extra load	The roof structure should be able to sustain the load of the rooftop garden infrastructure and pedestrian traffic in line with rain and snow.
Access to the rooftop	Facilitate internal and external staircases and elevators.
Safety	Design parapets around the building's edge.
Limited rooftop space	Consider sufficient space for mechanical systems and other essential equipment on the rooftop.
Building codes and legislation	Local building codes must be checked.
Proper insulation	Rooftops should be properly insulated and waterproofed.
Logistics	Transferring soil and other equipment might require a crane, which can be challenging.
Installation and maintenance cost	Consider installation and regular maintenance costs.
Social parameters	Sufficient space should be allocated for hosting a small to medium number of visitors.
Finishing surface	Depending on the climatic condition, the rooftop surface should be covered with anti-slip and frost-resistant tiles or a wooden deck.
Walking paths	Paths free of any barriers should be designed on the rooftop.
Lightning protection system	A lightning protection system might need to be installed on the rooftop.
Grouped mechanical systems	To clear the rooftop surface for farming, exhaust vents, mechanical systems, and equipment should be grouped together and installed in one corner of the roof.
Managing rainwater runoff	In order to remove rainwater effectively, the issue of slope should be considered.
Privacy	Future building residents should be willing to embark on farming activities which might interfere with their privacy.

Considering the proposed preliminary design recommendations, the three following farming methods can be developed on rooftops: (1) open-air rooftop food production, (2) "low-tech" rooftop greenhouses, and (3) "high-tech" rooftop greenhouse. Open-air rooftop farming consists of conventional cultivation methods such as rooftop container gardens, rooftop raised beds, green roofs, and vertical rooftop gardens. Soilless systems, such as hydroponics, can be installed on open-air rooftops. Conventional cultivation methods can be installed in “low-tech” rooftop greenhouses. Soilless systems, such as hydroponic systems, can be installed in controlled environments like “high-tech” rooftop greenhouses.

In this section, three design proposals are presented to illustrate various ways the three proposed farming methods can be applied in architectural designs. In design proposal one, open-air rooftop agriculture has been selected and developed. The mentioned design proposal utilizes soil-based cultivation methods such as container gardens, raised beds, and vertical gardens. Cold frames are utilized to extend the growing season. Trellises, metal cages, and teepees are added to the raised beds to support the plants. As mentioned, supports can create a living wall of vegetation on the rooftop. A trellis and a container are attached to the wall to allow the plants to grow vertically. Modular wall planters are attached to the south-facing wall to utilize the available vertical surface for cultivation. Lightweight containers are attached to the staircase railing. Wooden screens are designed to protect against the prevailing wind by deflecting it (Figure 16).

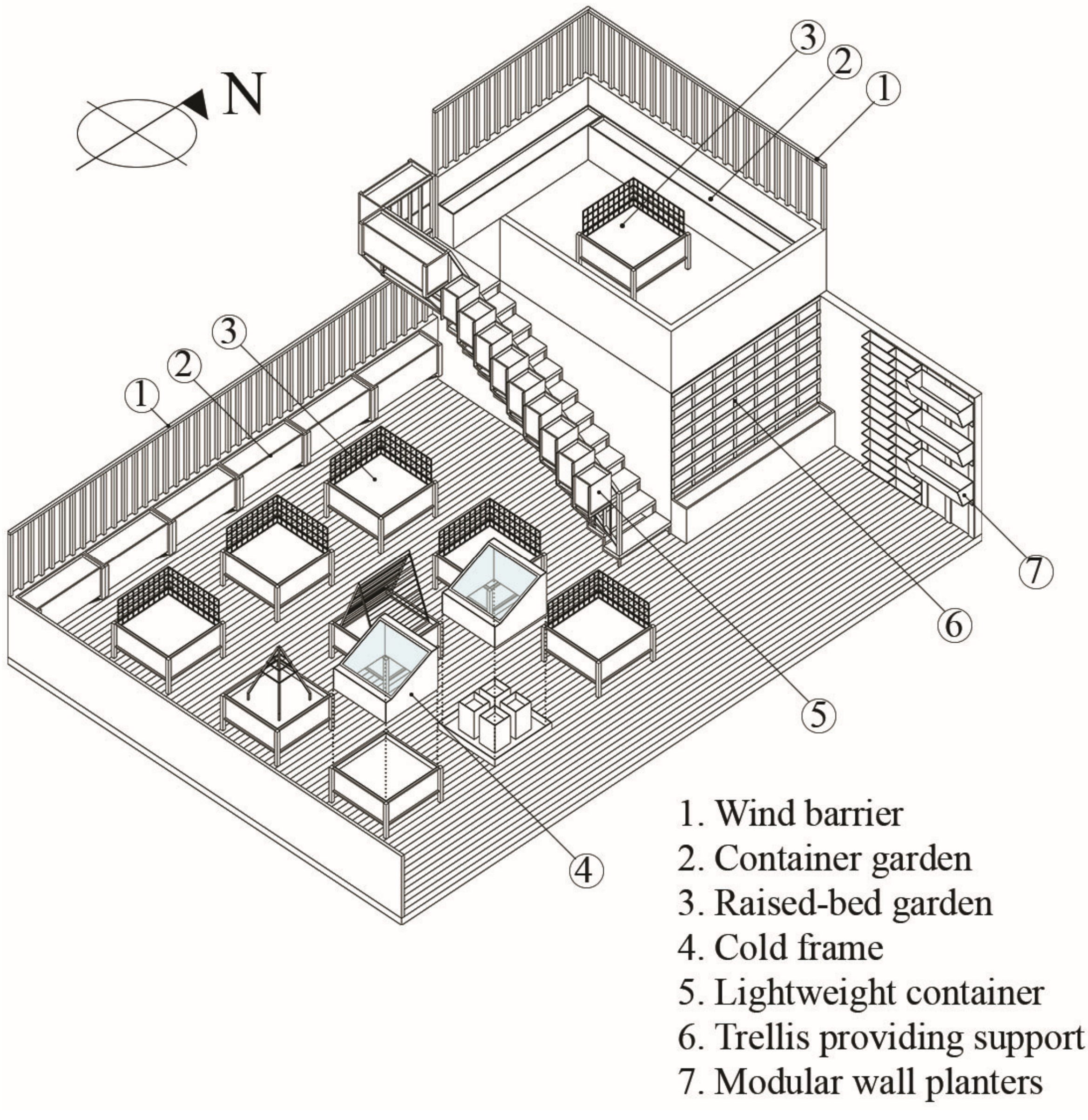

Figure 16. Design proposal one (developed by the author, 2023).

Design proposal two applies both conventional soil-based farming and “low-tech” greenhouses. Raised beds with teepees, metal cages, and trellises are designed inside the "low-tech" greenhouse. Like the previous design proposal, lightweight containers and raised beds are arranged on an open-air rooftop (Figure 17). In design proposal three, hydroponic systems are installed in a "high-tech" greenhouse. In addition to the "high-tech" greenhouse, lightweight containers and raised beds are also considered (Figure 18).

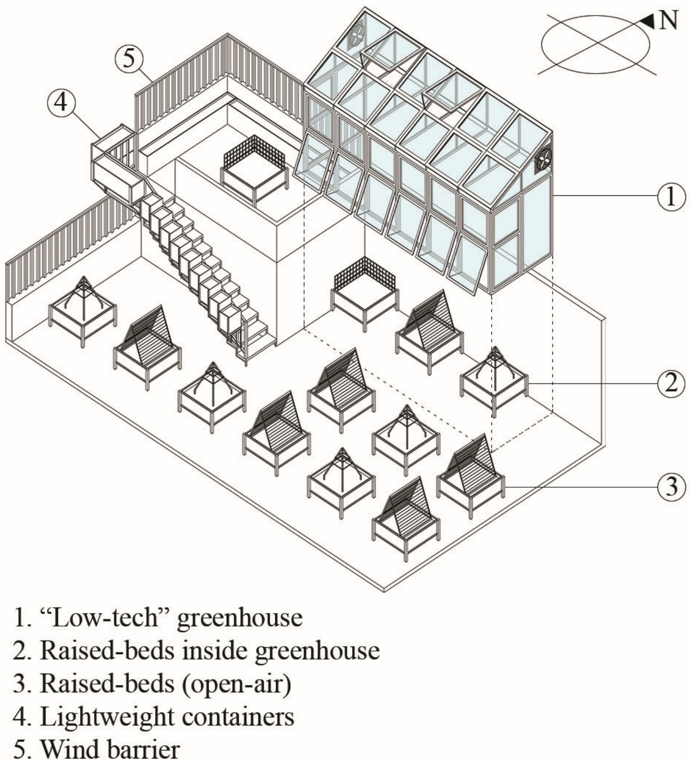

Figure 17. Design proposal two (developed by the author, 2023).

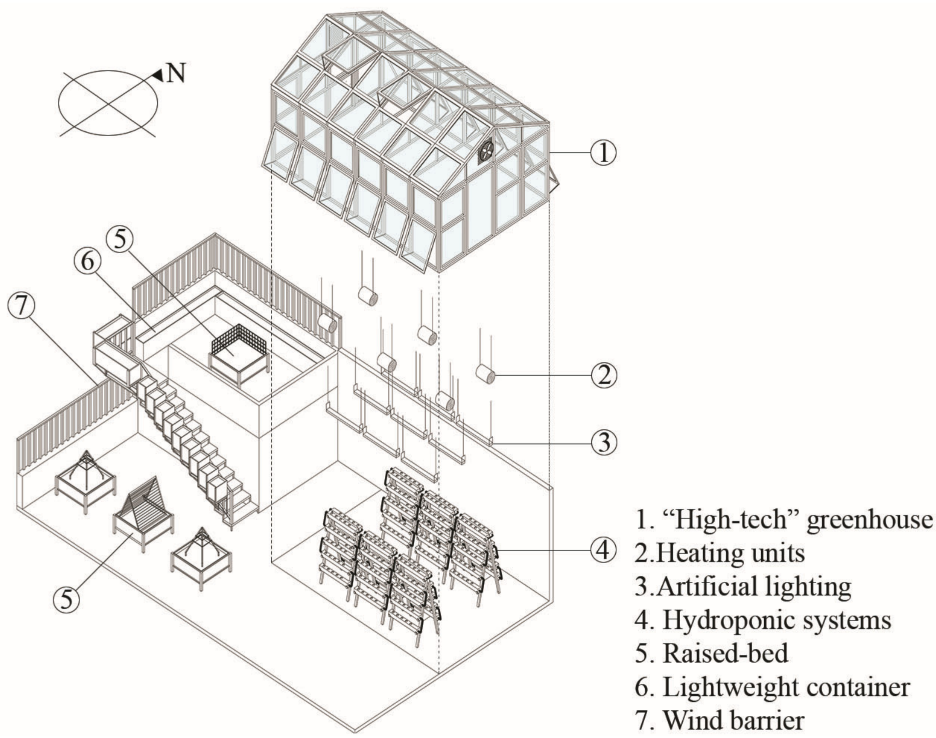

Figure 18. Design proposal three (developed by the author, 2023).

5. Discussion

Currently, the practice of urban agriculture is growing globally. Rooftop farming, as part of urban agriculture practices, also becomes an alternative option. In contemporary urban centers, allocating suitable land for urban agriculture is challenging. Rooftops can be considered an alternative option for scarce vacant land for food cultivation. New buildings can be designed so that their rooftops function as farms, and by doing that, such new buildings are becoming productive in cultivating crops and producing food [92].

Cultivating vegetables, fruits, and herbs on rooftops should not be regarded as a replacement for the large-scale crop production in rural areas. Rooftop cultivation should be considered a supplementary source capable of offering fresh local foods in dense urban areas [9,25,27,77,78,80,83,87,118,128,166,199]. By applying innovative methods of food cultivation, future cities will have the capacity to increase their self-reliance on food. By utilizing open-air farming and controlled-environment agriculture on vacant lands and rooftops, a considerable level of self-reliance in vegetables, fruits, and herbs can be achieved [32].

Rooftop container gardens, rooftop raised beds, green roofs, and vertical rooftop gardens can be considered open-air rooftop farming. Except for green roofs, container gardens, raised beds, and vertical gardens can be considered affordable methods to grow food. On the other hand, utilizing high-tech production techniques such as hydroponic systems in controlled environments such as greenhouses demands technical expertise and initial investments for setting up the rooftop farm. The methods mentioned usually consume more energy than conventional open-air rooftop farming. High energy consumption and initial investment costs can be considered major barriers to the extensive implementation of "high-tech" rooftop greenhouses [25,29,33,80,90,92].

As anticipated, urban growth and urbanization are inevitable. Agriculture production must increase soon to satisfy the growing population's food demand [25]. Innovative approaches should be considered for supplying fresh local food for current and future urban centers [25,28]. "High-tech" rooftop greenhouses as controlled-environment agriculture can be regarded as an innovative food cultivation method with the highest yield potential for future urban centers [36,200]. They can enhance city dwellers' access to local fresh vegetables, fruits, and herbs. They can contribute to local fresh food production in future urban centers [25,36,85,201].

Response to Research Questions

In response to research question one, "Which design recommendations should architects consider regarding designing residential rooftop farms?", the answers are provided in Section four. Regarding research question number two, "Which factors can be considered principal limitations when designing residential rooftop farms?", the following points can be considered limiting factors: (1) Climate: Open-air farming in regions with extreme cold and hot seasons can be a challenge. Extreme temperature fluctuations can have a negative effect on cultivation. (2) Sunlight: the rooftop surface might receive insufficient sunlight per day. (3) Wind: the rooftop might be exposed to excessive wind. (4) Shade: the neighboring buildings might cast shadows on the rooftop surface. (5) Water source: access to clean water for irrigation might be challenging. (6) Access to the rooftop: due to the privacy issue, access to the rooftop might not be granted by the residents. (7) Limited rooftop space: the rooftop surface might be occupied with mechanical systems and equipment; therefore, there might be insufficient space for cultivation. (8) Building codes and legislations: local building codes might limit rooftop farming. (9) Installation and maintenance cost: "Low-tech" and "high-tech" greenhouses require a high initial cost, which might be a burden for the user. The high cost of purchasing and installing hydroponic systems can be a challenge. (10) Energy consumption: "high-tech" greenhouses require energy. (11) Logistics: transferring soil, fertilizers, and farming equipment to the rooftop might be challenging. (12) Contaminated harvest: food cultivated in urban areas can be contaminated by the urban atmosphere. (13) Professional labor: inadequate access to professional labor can be a challenge. (14) Privacy: Farming activities such as the passage of farmers, equipment, technicians, inspectors, and visitors might conflict with the residents' privacy. Residents might object to such activities.

Benefits common to urban rooftop agriculture can be considered as follows: (1) Promoting local food production: rooftop farming promotes local food production, which decreases food miles and transport costs. (2) Promoting urban agriculture: it can assist city dwellers to reconnect with food cultivation in urban centers. (3) Optimizing the residential building's energy efficiency: It improves the roof's insulation; therefore, the energy requirement for cooling and heating the building is reduced. It can optimize the energy efficiency of the building. (4) Converting rooftops to productive grounds: rooftops, as unused or underutilized spaces, can be converted into productive grounds.

6. Conclusions

Based on current and future urban population growth, urbanization and urban growth are inevitable. The food supply demand of current and future cities is projected to grow, which will place additional stress on the agriculture sector to produce more food. Urban agriculture can be regarded as a remedy for possible future challenges that the global food system will face. It might be able to reduce the future burden on the agriculture sector. Urban rooftop agriculture can be regarded as a subset of urban agriculture. The rooftops of buildings in dense urban areas are unutilized spaces with direct exposure to sunlight, so they can be developed for cultivating fresh local food. Urban rooftop agriculture can become a crucial aspect of future food production in metropolitan areas.

This research highlighted a series of design recommendations for architects interested in designing residential buildings capable of cultivating food on their rooftops. In addition, this research also highlighted the principal factors that can be considered limitations with regard to designing residential rooftop farms. This research suggested that food can be cultivated via the following three methods on rooftops: (1) open-air rooftop food production, which is usually based on conventional soil-based cultivation methods; (2) "low-tech" rooftop greenhouses, which utilize simple cultivation methods in greenhouses without utilizing mechanized systems for controlling the indoor climate; and (3) "high-tech" rooftop greenhouses, which utilize soilless cultivation systems in greenhouses and utilize mechanized systems for heating, cooling, shading, and lighting.

In summary, this research highlighted that current and future buildings can be designed so that their rooftops function as farms. In this way, fresh local food can be cultivated on the rooftops of such buildings. By applying conventional and innovative cultivation methods in and on buildings, future cities will be able to produce local fresh food.

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