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Review

A Review of Research Progress in Vertical Farming on Façades: Design, Technology, and Benefits

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Abstract: The surging global population and urbanization trends present new challenges to food production systems and energy, especially in resource-limited urban environments. Vertical farming on façades (VFOF) is an innovative strategy to address this challenge by growing crops on building skins, efficiently using urban space, increasing food self-sufficiency, and reducing the environmental impact of carbon emissions. This article is a comprehensive review of VFOF and closely related topics based on 166 journal articles. It covers the latest research advances in design, technology, social impact, and environmental benefits. In addition to enhancing the autonomy of urban food supply and improving residents' quality of life, VFOF also has the potential to optimize the thermal performance of buildings and promote energy conservation by having some of the qualities of vertical greening systems (VGS). The planting system design and technical support factors for different façade locations are explained in detail. The symbiotic relationship between VFOF and architecture is examined to enhance sustainability. The popularity of VFOF is increasing in terms of social acceptance, and the government, together with the private sector and communities, play a vital role in promoting its development. In addition, this review also collates the cases of VFOF implementation in recent years. Research shows that the implementation of VFOF has many advantages, especially when considering future urban challenges under climate change scenarios and the need to provide solutions to achieve carbon neutral buildings and cities. Still, high initial investment, operating costs, technical complexity, security issue, policy and regulatory constraints, and public acceptance are all challenges to overcome. Further research should be carried out in the above fields.

Keywords: building façades; urban food production; sustainable urban development; carbon neutrality

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1. Introduction

1.1. Background

The COVID-19 epidemic mercilessly highlighted the weaknesses in the world's food supply chain [1,2]. In addition to exposing the flaws in the industrialized, capital-driven food system, the crisis made hunger and poverty worse, particularly for marginalized and

low-income populations [3]. Urban food systems need to be made more resilient because the majority of the food supply in cities is imported and susceptible to disruptions [4]. The demand for food has increased to unprecedented levels due to the world's population growth, which is predicted to reach nine billion people in the next 20 years [5]. Concerned about the conflict in Ukraine, which is a very important food producer and normally supplies food to 400 million people worldwide, Monika Tothova, an economist at the Food and Agriculture Organization [6], has alleged that food security challenges have been made worse by the war's disruption of international food supplies. Food production is becoming more and more isolated from urban consumers because of the increased demand for infrastructure to transport and distribute food to increasing urban areas. This globalized food system accounts for 29% of global greenhouse gas emissions [7]. The ability of diverse infrastructure systems to withstand shocks of varying magnitudes and durations has been referred to as resilience [8]. Urban resilience is a global issue, with North America and Europe having the highest levels of resilience, and African nations having the lowest [9]. Increasing environmental problems pose a danger to urban resilience, which is also defined as a system's capacity to anticipate, reduce, adapt, or recover from the impacts of catastrophic risks [10,11]. Climate change is making these problems more severe [12]. Anthropogenic drivers of global carbon emissions are predominantly attributed to the combustion of fossil fuels and the deterioration of land through processes such as desertification and deforestation [13]. Increasing carbon emissions and the effects of global warming on temperature and precipitation will affect crop yields and the area of land suitable for growing crops, resulting in significant socio-economic costs [14,15]. In this context, establishing cities with some degree of autonomy over vegetable crops and energy sources is crucial to building more resilient urban systems that can withstand potential shocks in the food supply chain on a global scale [16]. Vertical farming on façades (VFOF) is a promising solution to achieve this goal. The ratio of vertical to horizontal surfaces is rising as cities grow denser and have more high-rise structures; nevertheless, using these surfaces is frequently unproductive. It makes more sense to grow fresh food and fruits using building façades rather than taking up valuable inside space and devoting that space to other uses [17]. It also reduces the number of food miles associated with transportation, thereby reducing carbon emissions [18]. Crops can absorb the carbon dioxide produced by buildings [19] and mitigate solar radiation's impact on building surfaces and the urban heat island phenomenon, particularly when the shading effect is effectively managed [20]. In addition, VFOF enhances the urban living experience by fostering better health and social interactions among city residents, as indicated by [21,22]. They also contribute to poverty alleviation and reduced reliance on extensive food supply networks [23]. Figure 1 describes VFOF about related areas. It should be noted that vertical greening systems (VGS) focus on planting vegetation on the surface of the building, and vertical farming (VF) focuses on crop production within the vertical space. VFOF combines the characteristics of both, combining environmental benefits and food production functions. For example, VGS that can grow crops and VF types that can be planted on façades will be within the scope of this study.

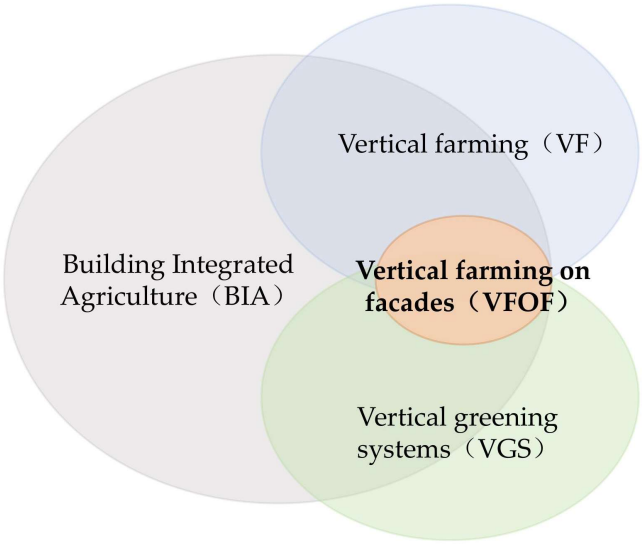


Figure 1. VFOF affiliations with related fields [17].

Urban home gardening and subsistence agriculture can significantly improve livelihoods, lessen the vulnerability of rural and urban households experiencing food insecurity, and slow the rate of increase in food prices [24]. Building-Integrated Agriculture (BIA) represents a cutting-edge approach to food cultivation, predicated on the synergistic relationship between advanced agricultural technologies and architectural structures [16]. This system is distinguished by its recirculated hydroponic operations that harness surplus thermal energy from the building's HVAC systems and renewable energy sources such as photovoltaic panels and also incorporates rainwater harvesting mechanisms along with evaporative cooling techniques [25]. Because it reduces food miles [18], uses less land and water [26], and increases yields [27], BIA is a concept in agriculture that is considered to be more environmentally sustainable than conventional agriculture. Nevertheless, urban BIA, while considered sustainable and capable of reducing transportation distances, may not be suitable for all sites since their food miles reduction does not consistently counterbalance its high energy demands [28]. VF represents a contemporary form of UA that capitalizes on the vertical space of urban buildings and employs soil-free cultivation techniques to produce crops [29]. Complementing conventional farming practices, VF optimizes urban space utilization, mitigates conflicts between urban farming and urban land usage, and has the potential to become an integral component of the local food system [30]. A promising variant of the VF system, VFOF uses solar energy on surfaces that have already been built upon while incorporating new technology advancements such as Building Integrated Photovoltaic (BIPV) systems as in the case of the Productive Façade Systems [31,32]. VF can be used on the building's façade and roof, as well as inside the structure.

Plants grown on the front, top, or side of a building or feature wall are known as VGS [33]. The principles and practices of VGS have gained momentum in the last few decades. Therefore, their developed technologies have also been applied for growing food on façades. However the VGS is solely focused on growing decorative plants [17]. Incorporating vegetation on underutilized architectural façades serves as a method for harmonizing urban areas with greenery [34]. This addresses the issue of urban people's lack of access to ground-level public green space because of the high cost of land and dense population [35,36]. Depending on how they are grown, VGS are typically classified as "green façades" or "living walls" [37,38]. Green façades consist of climbing plants growing from the ground or on growers utilizing trellises or directly on the building surfaces. On the other hand, plants grown in pots or on modular panels are referred to as living walls. The plant, the medium, the irrigation system, and the system (container) are their

fundamental parts. The classification of VGS is somewhat different from study to study and is summarized in Table 1. Making use of a building's façade area for greening has become a highly popular approach. The service benefits of vertical greening have now been extensively researched [39]. The potential and efficacy of using VGS can enhance building thermal performance and energy efficiency [40,41], as well as lessen the effects of climate change in urban areas [42].

Table 1. A summary of some research on the classification of VGS.

Year	Study	Classification	Ref.
2022	VFOF	1. Single layer (conventional façades): balconies, corridors, terraces, curtain walls, windows, bare, platform overhang, scaffold. 2. Double skin: indoors, inside cavity, single layer, multiple layer.	[17]
2011	VGS	1. Green façades: planted into the soil and planted in planter boxes. 2. Wall vegetation: natural vegetation and prefabricated panels for vegetation. 3. Living wall systems: prefabricated and in situ.	[43]
2017	VGS	1. Green façades: direct green façade and double-skin green façade. 2. Green walls: continuous green wall, modular green wall and linear green wall.	[44]
2019	VGS	1. Direct greening. 2. Indirect greening. 3. Modular.	[39]
2023	VGS	1. Green façade: direct green façade and indirect green façade. 2. Living wall: continuous living wall and modular living wall.	[45]

Adaptation experiments were carried out by Abd Ghafar et al. [46] on plant species cultivated under vertical greening; nevertheless, the majority of these plants were ornamental. Research on edible plant-based VGS has also been done [47]. UA can flourish with a more comprehensive and adaptable solution when VGS is used in tandem with production. Studies frequently identify VFOF as a component of home gardening. Home gardening can be done in underutilized vertical areas found in apartment buildings, such as balconies, corridors, façades, and roofs [48]. The majority of the home gardening literature has focused on home and community gardens, including those in Madison [49], Oman [50], and some cities where production levels are high enough to be commercially grown [51]. Crops grown vertically are seen as fresh enough to be sold as organic in nations like the United States [52]. Moreover, vertical gardens can modulate building temperatures, improve air quality, control light levels within buildings, or serve as attractive architectural art features. Incorporating novel architectural features into newly constructed or renovated buildings to help lessen the effects of adverse environmental circumstances [53].

Many studies have measured and modeled solar exposure on building façades, aiming to assess the feasibility of growing vegetables on such surfaces by considering their directional orientation and the context of their urban setting. In particular, studies conducted by Tablada and Zhao [54] have shown that, in Singapore, theoretical residential structures with varying degrees of urban concentration have façades that receive sufficient solar exposure for cultivating leafy greens. The viability of employing façades for vegetable growing in Singapore's public housing was shown by Song, Tan, and Tan [55]. Based on measured Daily Light Integral (DLI) and photosynthetically active radiation, it was discovered that vegetables may be produced successfully with half a day of direct sunshine. Palliwal, Song, Tan, and Biljecki [56] used a 3D city model to perform environmental simulations to identify suitable agricultural locations on residential building façades. Although the model only applies to Singapore, it applies at the city level at any latitude and climate. In addition to their widespread use in residential buildings, VFOF has numerous research

applications in other building types [17]. Global adoption of VFOF would alleviate the threat of hunger and reduce the environmental consequences caused by climate change [57]. The advantages of VFOF are enumerated in Table 2. However, cultivation on or within buildings may be prohibited by current laws and regulations [58]. Even if more people are becoming interested in learning about VFOF, there are still challenges to cope with before an expensive use of VFOF. This review is intended to complement existing VFOF review studies, focusing on recent advances in the design, technology, and environmental benefits of VFOF. In addition, this review explores the role of VFOF in achieving carbon neutrality goals in buildings and cities, which is an important addition to existing research. Through these discussions, we aim to promote the practical application and future research of VFOF.

Table 2. Summary of the advantages of VFOF.

Category	Advantage	Ref.
Social and economic benefits	Be very beautiful and can protect the wall against graffiti	[31]
	Positive impact on user health and well-being	[31,59]
	Increased thermal and visual comfort inside the building	[31,41]
	Positive impact on local economy, food security, and self-sufficiency	[59]
	Increased social sustainability and enriched social life of users	[18]
	Improved aesthetics of the building	[31]
Energy and environmental benefits	Improve air quality	[43]
	Provide sound insulation	[60]
	Improve the thermal performance of building envelope structures	[61]
	Create a microclimate, which will help to alter the climate of a city as a whole	[62]
	Reduce the carbon footprint of carbon absorption in vegetable transportation and other areas	[19]

1.2. Objectives and Article Structure

Multiple reviews have contributed significantly to advancing the VGS and VF knowledge framework, as shown in Table 3. On the other hand, little emphasis has been paid to scientific advancements in VFOF. This research focuses on the design level of VFOF and attempts to provide a thorough review to add to the body of information already in existence. As a relatively new concept, VFOF has not been widely recognized in the research field, but it is worth noting that VFOF integrates the characteristics of VF and VGS and can be regarded as a part of VF and VGS. This article collects some relevant publications that conform to VFOF, which can reflect its scientific value. The paper is structured as follows: Section 2 describes the article's research methodology for a systematic literature review of VFOF. Sections 3.1 and 3.2 summarize the design and technical aspects of VFOF based on relevant studies. Section 3.3 explores the yield and environmental benefits of VFOF. Section 3.4 summarizes the impact of the governmental and societal dimensions on VFOF. Section 3.5 organizes the safety issues involved in VFOF. Section 3.6 summarizes VFOF cases based on those implemented today. Finally, we discuss VFOF research and the outlook, including the formative product design level, the benefit assessment level, and the dissemination level.

Table 3. Reviews of recent studies related to VGS and VF.

Year	Author	Objective	Ref.
2014	Specht	Exploring the role of Zfarming based on a sustainability framework	[18]
2017	Kalantari	The technology and skills of Vertical Farming	[63]
2018	Al-Kodmany	The technology and benefits of Vertical Farming	[59]
2018	Zaid	The benefits and carbon sequestration potential of Vertical Greenery System in tropical regions	[64]
2021	Halgamuge	Vertical cultivation walls based on Internet of Things and autonomous control	[5]
2022	Yuan	Research on technology, socio-economic and policy based on Urban agriculture	[65]
2023	Gamal	Environmental benefits of Vertical Greenery System under humid and hot conditions	[45]
2024	Su	The thermal effect mechanism of Vertical Greenery System	[66]

2. Methods

We conducted a comprehensive literature review on VFOF, which allowed us to conduct an in-depth analysis of all available evidence under a particular topic, assess the quality of the evidence, and synthesize the results to provide comprehensive insights. To collect relevant studies, the literature search was conducted using databases such as Web of Science, Scopus, ScienceDirect, and Google Scholar, combined with Boolean operators such as And/Or. Before searching, we first identified keywords by initially reviewing the academic literature related to VFOF, including previous reviews, seminal articles, and key reports. Subsequently, the keyword list is further screened and refined by combining terms from different disciplines. Because terms with the same meaning may be expressed in different ways, synonym integration is carried out to ensure comprehensiveness of the search. The period of the data collection was January 2014–July 2024, which ensured the timeliness and comprehensiveness of the data collection. Step 1 was a keyword search, including: "vertical farming on facade", "vertical garden", "facade farming", "home gardening", "building facade planting", "productive facade", and "vertical greening system". A total of 6916 articles were obtained. Step 2 for keyword search must include "facade". Then, 332 articles were selected. Step 3 excluded duplicate, non-English, non-peer-reviewed articles, conference papers, and opinion articles, resulting in 249 articles. Then, was the inevitable element of subjectivity. Step 4 read the title of the article by the author and exclude irrelevant articles. A total of 37 articles were excluded, and 212 articles were selected. Step 5 was for the author to read the abstract and the full text of the article and exclude irrelevant articles based on the author's subjective judgment. This exclusion criterion was also subject to the authors' subjective decisions, such as the types of VGS that could not grow crops, the supply chain of VF, logistics distribution, and large-scale commercial vertical farm operations, focusing on indoor VF systems as the leading research, as these aspects usually do not involve the direct application of building façades. Finally, 166 articles were selected for in-depth analysis (Figure 2). Then, the open-source software "VOSviewer 1.6.20" was used to conduct keyword co-occurrence analysis on the bibliometrics data of the search results related to 166 articles after screening, and the words with at least 10 keyword repeats were selected to visually represent the outcomes of the analysis. Results indicated that a total of 27 keywords were obtained. Among these, the keywords that have been most frequently associated with VFOF in recent studies include: (1) green facade, (2) thermal performance, (3) buildings, (4) living wall, and (5) facade, as shown in Figure 3. The figure also shows that the research related to VFOF is increasing year by year, with more research on VGS and energy efficiency and less research related to VF.

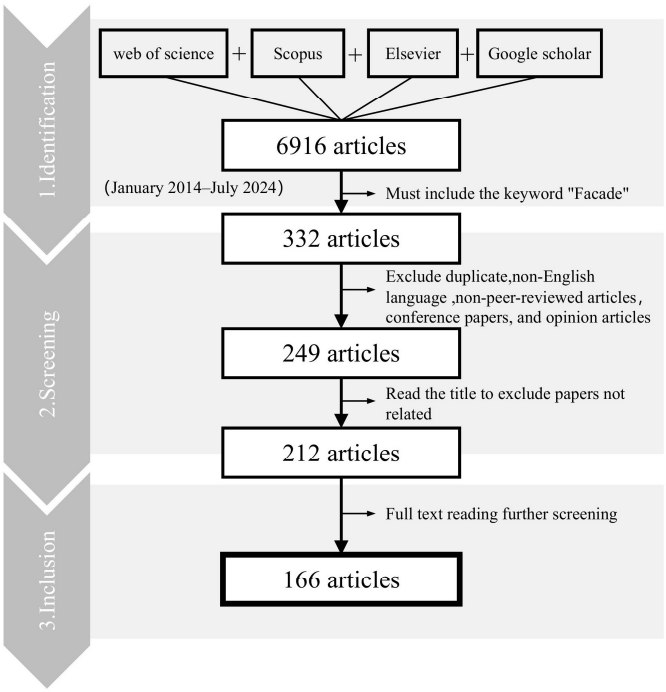


Figure 2. The process of article selection in the review. Source: the authors.

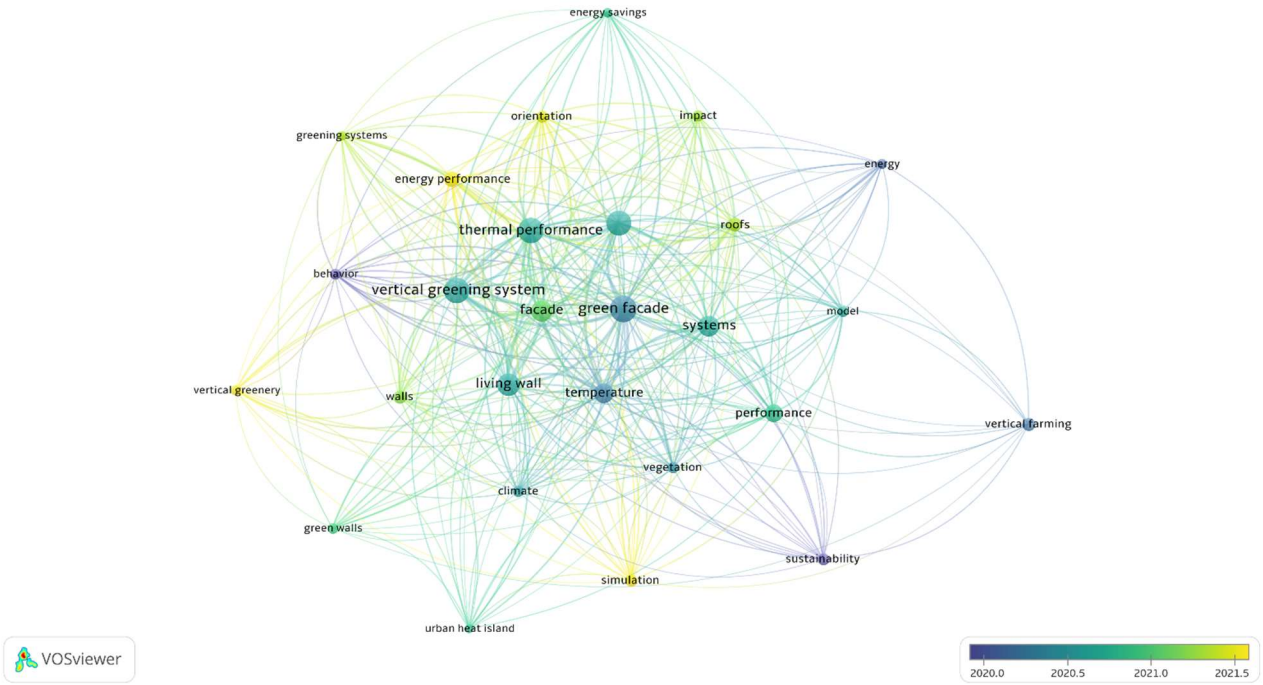


Figure 3. Composite graphical representation of the co-occurrence analysis for all identified keywords. Source: the authors.

3. Results

3.1. Multi-Dimensional Considerations at the Design Level

3.1.1. Different Façade Locations and Types

Through integrating VF and VGS technologies, VFOF demonstrate considerable versatility and application potential. The VFOF is categorized in Table 4 based on its façade positions; the classification names are derived from these places to facilitate differentiation. This is due to the lack of a thorough, defined name system for the various kinds of VFOF in the relevant literature. These systems are carefully grouped based on multiple façade

locations, including windows, balconies, terraces, double-skin façades (DSF), and bare walls [17]. Each classification complies with particular technical and design specifications to meet various goals, including accessibility, safety, productivity, and aesthetics.

Around the world, many urban and suburban buildings have started to use their balconies and walls to grow vegetables, herbs, and flowers [17]. For homes without private gardens, this approach offers excellent gardening prospects. In contrast to conventional home gardening practices that are soil-dependent and require manual watering, façade farming's flexibility allows it to be integrated with different types of building façades and serve a variety of building purposes, from residential to office and commercial. This is possible because of its decentralized, open-source, small-scale, and diverse nature [17]. Façade farming not only contributes to food security in urban areas [67], but through centralized digital management, it also helps to reduce the operational costs and energy consumption of implementing vertical agricultural systems in office, commercial, and industrial buildings [17]. The notion of digital UA has evolved due to the application of automation and artificial intelligence technology in agriculture [68], further improving the intelligence and efficiency of agricultural production.

By placing plant coverings within the building façade, DSF improves the planting space and enhances the structure's thermal performance [69,70]. In addition, exposed walls offer climbing plants ideal growing circumstances, while mesh frames and other support systems encourage vertical growth [71]. To obtain plant cover on building surfaces, LWS frequently have modular designs and use panels or containers [37,38].

Existing studies have enriched different façade location design options for VFOF, but most have not been thoroughly studied, such as the system's rationality under different conditions. Future studies can further explore these aspects through long-term field tests and other methods.

Table 4. Classification of different elevation positions of VFOF [17,43–45,48,72].

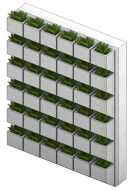
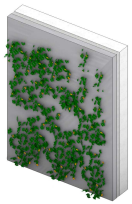
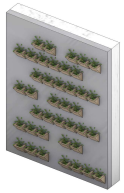
Classification			Illustration	Location	Plants Species	Irrigation System	Features
VGS	Living wall system (LWS)	Linear LWS		Walls	Freestanding potted plants	Automatic irrigation	Linear planting containers are mounted on the wall, positioned vertically, with each tier placed above the previous one.
		Modular LWS		Walls	Freestanding potted plants	Automatic irrigation	The system comprises multiple units configured as pouch-like plant containers and panels. Each unit is engineered to accommodate soil or a growth medium and is secured to the rear of the framework.
		Continuous LWS		Walls	Freestanding potted plants	Automatic irrigation	Referred to as "vertical gardens", they are composed of a dual-layer synthetic fabric structure featuring compartments designed to hold growing medium for individual plants.
Farming façades	Single layer	Platform overhang		Blind walls	Freestanding potted plants	Artificial nature, or automatic irrigation	Hanging the planting box on the exterior wall has a positive impact on the building envelope structure.
		Scaffold		Blind walls	Freestanding potted plants	Artificial nature, or automatic irrigation	Hanging the planting box on the exterior wall has a positive impact on the building envelope structure.

Table 4. *Cont.*

Classification			Illustration	Location	Plants Species	Irrigation System	Features
Farming façades	Single layer	Indoors		Windows	Freestanding potted plants	Artificial nature, or automatic irrigation	The indoor window is hung with a planting box for growing vegetables.
		Outdoors1		Windows	Freestanding potted plants	Artificial nature, or automatic irrigation	The planting box is hung outside the window for growing vegetables.
		Outdoors2		Windows	Freestanding potted plants	Artificial nature, or automatic irrigation	The window frame is fitted with a planting system for growing vegetables.
		Integrated 1		Balconies	Freestanding potted plants	Artificial nature, or automatic irrigation	Utilizing balcony space to install planters and enhance the outdoor environment
		Integrated 2		Balconies	Freestanding potted plants	Artificial nature, or automatic irrigation	Additional planting platforms outside the balcony not only play a landscaping role but also benefit the outdoor Environment.

Table 4. *Cont.*

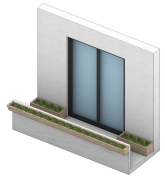
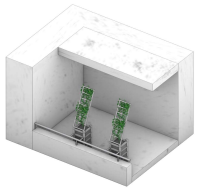
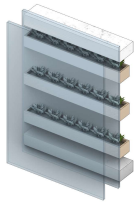
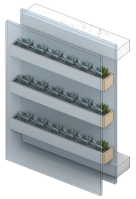
Classification			Illustration	Location	Plants Species	Irrigation System	Features
Farming façades	Single layer	Integrated 3		Balconies	Freestanding potted plants	Artificial nature, or automatic irrigation	Extra planting shelves beyond the balcony serve not only an aesthetic purpose but also enhance the surrounding outdoor atmosphere.
		Removable pots		Balconies	Freestanding potted plants	Artificial nature, or automatic irrigation	Utilizing balcony space to install planters and enhance the outdoor environment
		Multiple layer		Sky gardens	Common fruit trees	Artificial nature, or automatic irrigation	Planting fruit trees in a multi-level terrace space can not only enrich the landscape but also improve the quality of the built environment.
		Vertical gardening systems		Corridors	Freestanding potted plants	Artificial nature, or automatic irrigation	Install several vertical, multi-level garden prototypes equipped with adjustable frameworks along the building's hallway. The framework allows the grille to be repositioned from an upright orientation to a lower level for convenient maintenance and enhanced safety.
	Double skin	Indoors		Curtain walls	Freestanding potted plants	Artificial nature, or automatic irrigation	Place planting systems near the curtain wall, with plants in trays on a simple cable system, allowing all planting and harvesting at the bottom level.

Table 4. *Cont.*

Classification			Illustration	Location	Plants Species	Irrigation System	Features
Farming façades	Double skin	Inside cavity		Curtain walls	Freestanding potted plants	Artificial nature, or automatic irrigation	Integrate the planting system within the double curtain wall, with plants on suspended trays via a basic cable setup, facilitating ground-level planting and harvesting.
		Suspended façade		Windows	Freestanding potted plants	Artificial nature, or automatic irrigation	Hanging plates are attached to the outside of the wall, and the hanging plates are equipped with planting grooves for growing crops.

3.1.2. System Component Design

The design of system components for VFOF is critical to realizing an effective vertical farming system. Table 5 synthesizes research on the design of components involved in planting on different elevations, and we gained insight into the specific applications and design presentations of planting components in different research projects. Walls, balconies, windows, and corridors are among the various construction styles used for planting elements. For instance, studies conducted in Singapore's residential buildings have investigated the viability of façade planting for food production using soil and soilless media [48]. A commercial hanging planter system was employed in one study, and a multi-story vertical corridor gardening prototype was created by modifying a Toyo® cabinet (model 802-5). These studies aimed to enhance the viability of food production while simultaneously optimizing space utilization. Furthermore, various innovative façade planting schemes, like those found on balconies in Hanoi, Vietnam, and other places, show how small areas can be used to combine decorative and functional purposes. These systems frequently have rain protection and shading features, which enable various configurations and daylight regulation, exhibiting versatility and adaptation in different environmental circumstances [73].

Table 5. Related studies involve planting system components.

Type	Picture	Location	Study Area	Growth Medium	Experimental Purpose	Introduction	Ref.
Corridor		Singapore	Residential building	Soil	Potential of food production	A commercially available hanging trough planting system, model BABA®, Model BI-509 Planter Box, Malaysia, which measured 48.9 cm × 18.7 cm × 15.6 cm.	[48]
Corridor		Singapore	Residential building	Soilless medium	Potential of food production	The prototype was transformed from a Toshiba® cabinet (model 802-5), which measured 43 cm × 33 cm × 107 cm.	[48]
Window		Singapore	Tropical Technologies Laboratory	Soilless medium	Potential of food production	Two rows of PlanterCell® Model 170 flowerpots from Uniseal, Singapore, measuring 50 cm × 15 cm × 17 cm, with 2–3 planters per row, were installed on railings.	[31,74]
Window		Shanghai, China	Residential building	Soilless medium	Potential of food production	Two urban household vertical farming prototypes, 143 cm long.	[75]

Table 5. *Cont.*

Type	Picture	Location	Study Area	Growth Medium	Experimental Purpose	Introduction	Ref.
Balcony		Penang, Malaysia	Residential building	Soil	Thermal properties of edible VGS	A support system made of steel mesh (2.1 m × 1.8 m × 0.15 m) to guide the edible plants upward to achieve the desired leaf density.	[47]
Balcony		Singapore	Office Building	Soil	Potential of food production	Common transparent plastic cups were added with substrate fixed on a grid to form vertical arming consisting of multiple layers of stacked plants.	[76]
Wall		Singapore	Factory	Soil or water	Food production	The system consisted of a rotating growth groove layer mounted on an A-shaped aluminum frame. The frame could be as high as 9 m and had 38 layers of growth tanks.	[77]

Table 5. *Cont.*

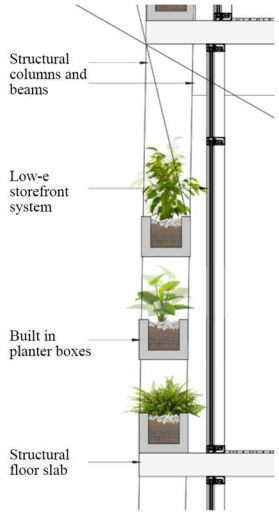
Type	Picture	Location	Study Area	Growth Medium	Experimental Purpose	Introduction	Ref.
Wall		Auckland, New Zealand	Tower	Soil	Food production	These planting boxes were fixed between the surrounding columns and spanned the façade.	[78]
Wall		Lagos, Nigeria	Single-story house	Soil	VGS affordability in low-income communities	High-density polyethylene (HDPE) and bamboo were two different material types to accommodate plants and their substrates.	[23]
Façade		Nablus, Palestine	Residential building	Soilless medium	Potential of food production	The modular adaptive façadesystem included LED, PV, sensor, fan.	[79]

Table 5. *Cont.*

Type	Picture	Location	Study Area	Growth Medium	Experimental Purpose	Introduction	Ref.
Scaffold		London, Britain	School building	Soilless medium	Potential of different LWS and growth media	• Left: It consisted of 49 flexible "industrially produced flexible multilayer modules". • Right: The 40 pots were individually connected to stainless-steel-reinforced mesh plates.	[80]
Double skin		London, Britain	Office Building	Soilless medium	Potential of food production, energy efficiency, and environmental impact	An integrated hydroponics system and fish farming were placed inside the double curtain wall.	[81]

The selection of component materials, dimension design, and integration with the building's existing structure are all important considerations when creating a façade planting system. For instance, in their façade planting studies, Wang et al. [82] selected a planting slot size of 0.2 m × 0.2 m, which corresponded to the window size module. For best efficiency, the planting spacing of 0.25 m might be placed continuously along the vertical plane or in layers with vertical spacing of at least 400 mm. According to Tablada et al. [83], pots with a multi-tiered design should possess a trapezoidal profile to afford the bottom plants ample room for growth and enhanced sunlight exposure. A minimum vertical separation of 0.4 m between the planting beds is recommended. In contrast, the planting box system created by Greenwave systems employs recyclable HDPE plastic modules reinforced with fiberglass. Each module is 600 mm in width, 515 mm in height, and 200 mm in depth. These modules are flexible enough to accommodate various plants' growing requirements and are solid and long-lasting [43]. These designs highlight the significance of maintenance, as it can impact the selection of plant species and system types.

The Continuous LWS usually includes a frame to hold the subfloor in place and protect the walls from moisture. A fabric layer, serving as an absorbent, flexible, and root-resistant screen with drainage capabilities, is applied to the growing medium. The hydroponic system supplies the plants with the necessary water and nutrients. The fabric is secured to a waterproof membrane to shield the building materials from dampness [84,85]. The modular LWS comprises multiple units configured as pocket planters and panels. Each unit is engineered to contain soil or a growth medium and is affixed to the supporting framework [85]. The linear LWS consists of linear planting boxes (such as aluminum or plastic (HDPE)), one on top of the other, and filled with a substrate (such as soil or mineral pellets) [84,86]. A study of VGS prototyping and construction in a low-income neighborhood in Lagos, Nigeria [23], is of particular interest. This research highlighted the dual role of VGS in enhancing indoor thermal comfort and serving as a substrate for the cultivation of plants with both edible and medicinal properties. By working with the local community, the research team developed VGS prototypes that were economical and easy to prototype, which reduced indoor temperatures and provided up to 16 crops per year. Community acceptance of VGS has been very high, demonstrating that VGS can be an adequate food and environmental solution in communities with limited resources. However, this study was carried out in low-rise residential buildings, and there may be limitations if it is generalized in high-rise buildings. The complex structure of tall buildings may limit their direct application, and further research and innovative design are needed to overcome these obstacles. At present, the existing research provides a variety of solutions for the design of VFOF system components. Still, many of them are used for research and testing, the components themselves are not easy to manage, and durability problems need to be further optimized.

3.1.3. Plant Options

In VFOF systems, choosing the suitable plant species is crucial to achieving effective agricultural production. The appropriate crops for VFOF and relevant information are provided in Table 6. The size of the planter, plant rows, plant spacing, and plant variety for VF systems on a façade must be chosen based on the particular requirements of the crop and the building's window size [82]. Presently, VFOF predominantly consists of low-tech setups on balconies and open verandas operated by families. These systems have demonstrated feasibility owing to their straightforward design, adaptable installation processes, and the modest aspirations of the farmers involved.

When selecting plant species, the assessment should be made according to the climatic conditions of the region, taking into account local factors such as light, temperature, and

humidity [60]. Climate has a significant impact on plant growth and development, so cultivating fruits, herbs, and leafy greens that are adapted to the local climate is crucial for open-air farming [17]. In the realm of façade farming, small leafy greens are predominantly cultivated due to their enhanced productivity, convenient harvesting, and effective utilization of space. The brief period from sowing to harvest contributes to their high profitability and the adaptability of cropping systems and crop variety selection [87]. Since leafy vegetables have short root systems and are edible throughout, they are typically recommended for VF [31]. However, due to the potential shadowing effect between buildings, which can result in a significant reduction in sunshine, shade-tolerant crops with relatively low light requirements, like lettuce and water vines, are advised for planting on building façades [82]. Lettuce can thrive in settings with reduced light levels, specifically between 4 and 10 DLI, due to its inherent shade tolerance and low cumulative daily light exposure [88], although 12–13 mol/m^2·day or greater DLI is necessary for its ideal growth conditions [89]. Except for leafy vegetables, bean sprouts require relatively little or no light and have a much shorter growth cycle [90]. Plant selection for VGS has evolved from ornamentals to edibles that can yield multiple benefits [47]. The most effective legumes, for instance, were employed by the study teams of Abdul Rahman et al. [91] and Amir et al. [92] as part of a wall vertical greening system, which improved thermal performance and gave the occupants a source of food. The study included edible legumes such as kidney bean (*Phaseolus vulgaris*), winged bean (*Psophocarpus tetrogonobulus*), long bean (*Vigna unguiculata sesquipedalis*), and sweet pea (*Pisum sativum*). In addition, the ecological benefits and environmental adaptability of plants are important bases for selection. Some plants not only bring agriculture but also clean the air, reduce noise, and regulate the microclimate. Selecting plants with high stress tolerance, such as drought-, pest-, and disease-resistant varieties, can reduce resource consumption and environmental risks.

In Controlled Environment Agriculture (CEA), the choice of crops is predominantly shaped by the artificial environmental conditions created by the technology in use; these settings may extend from tailored extremes for specific crops to air-conditioned spaces typical of commercial and residential areas [17]. For instance, crops that grow well in temperatures from 17 °C to 28 °C, like tomatoes, peppers, and cucumbers, have moderate temperature requirements [93,94].

Table 6. A list of crop species selected for planting residential building façades. (Note: × less, ×× middling, ××× sufficient) [23,48,54,75,95,96].

Vernacular Name	Botanical Name	Source	Typical Growth Period	Suitable Temperature	Adaptability	Light Demand
Chinese spinach	*Amaranthus tricolor*	Seed	25–28 days	15–30 °C	Cold tolerance	×××
Water spinach	*Ipomoea aquatica*	Seed	20–25 days	15–20 °C	Cold tolerance	×××
Snow pea sprout	*Pisum sativum* var. saccharatum	Seed	7 days	15–20 °C	Cold tolerance	×××
Onions	*Allium cepa*	Cutting	330 days	15–25 °C	Cold tolerance	×××
Gooseberries	*Ribes burejense* F. Schmidt	Cutting	1 year	15–30 °C	Cold tolerance	×××
Parsnips	*Pastinaca sativa*	Seed	120–180 days	20–25 °C	Cold tolerance	×××
Spring onions	*Allium fistulosum*	Cutting	30 days	13–25 °C	Cold tolerance	×××
Beetroot	*Beta vulgaris* L. var. rapacea Koch	Cutting	70 days	15–25 °C	Cold tolerance	×××
Blackberry	*Rubus fruticosus*	Cutting	1 year	20–30 °C	Cold tolerance	×××
Rhubarb	*Rheum* × *hybridum*	Cutting	1 year	15–22 °C	Cold tolerance	×××
Oyster mushroom	*Pleurotus ostreatus*	Spawn	10–14 days	24–27 °C	Cold tolerance	×
Bitter gourd	*Momordica charantia*	Seed	60 days	20–30 °C	Heat resistance	×××
Long bean	*Vigna unguiculata*	Seed	55 days	20–30 °C	Heat resistance	×××
Pumpkin	*Cucurbita moschata*	Seed	110 days	18–32 °C	Heat resistance	×××

Table 6. *Cont.*

Vernacular Name	Botanical Name	Source	Typical Growth Period	Suitable Temperature	Adaptability	Light Demand
Sweet potato vine (green)	*Ipomoea batatas* (green-stemmed cultivar)	Cutting	30 days	20–30 °C	Heat resistance	×××
Sweet potato vine (purple)	*Ipomoea batatas* (purple-stemmed cultivar)	Cutting	30 days	20–30 °C	Heat resistance	×××
Corn	*Zea mays*	Seed	100–130 days	22–30 °C	Heat resistance	×××
Winged bean	*Psophocarus tetragonolobus*	Seed	60–70 days	20–25 °C	Heat resistance	×
Potatoes	*Solanum tuberosum* L.	Cutting	60–100 days	17–21 °C	Gentleness	×××
Cucumber	*Cucumis sativus*	Seed	35 days	18–32 °C	Gentleness	×××
French bean	*Phaseolus vulgaris*	Seed	45 days	21–29 °C	Gentleness	×××
Malabar spinach (green)	*Basella alba* (green-leafed cultivar)	Cutting	50 days	15–27 °C	Gentleness	×××
Malabar spinach (red)	*Basella alba* (red-leafed cultivar)	Cutting	50 days	15–27 °C	Gentleness	×××
Tomatoes	*Solanum lycopersicum*	Seed	110–170 days	20–25 °C	Gentleness	×××
Strawberries	*Fragaria* × *ananassa*	Seed	180 days	18–25 °C	Gentleness	×××
Choy sum	*Brassica rapa* Cultivar Group Caisin	Seed	28–30 days	15–25 °C	Gentleness	××
Runner beans	*Phaseolus coccineus*	Seed	60–70 days	15–25 °C	Gentleness	××
Chinese Cabbage	*Brassica rapa* pekinensis	Seed	55 days	10–22 °C	Semi-cold tolerance	×××
Carrot	*Daucus carota*	Seed	180 days	15–25 °C	Semi-cold tolerance	×××
Pea	*Pisum sativum*	Seed	65–75 days	15–25 °C	Semi-cold tolerance	×××
Lettuce	*Lactuca sativa*	Seed	50–70 days	15–20 °C	Not tolerant of cold and heat	××

3.1.4. Measuring and Model Prediction Methods

Through investigating the forecasting of outcomes from VFOF experimental investigations, scholars have formulated various techniques to assess these systems' capability and effectiveness in real-world scenarios. Among them, Song et al. [48] designed a prototype vertical growing system to select suitable plants and growing media by measuring DLI obtained from photosynthetically active radiation (PAR) sensors and predicted annual yields using 3D models and standardized harvest data. This approach provides a scientific basis for assessing the potential of UA. Furthermore, Hao et al. [74] introduced an innovative forecasting method that leverages experimental data to educate an artificial neural network (ANN). Then, experimental data will be inputted to the ANN and processed to forecast yields under the effect of various architectural and environmental elements in a timely and accurate manner. Grasshopper plug-ins and Rhinoceros 6 3D software were used to construct this system platform, which offers an effective technological instrument for prediction. However, the predictions need to be verified by actual crop yield measurements. Researchers often measure the fresh weight of harvested crops at the end of the growing cycle to assess the crop's annual yield [48,75]. In addition, Hao et al.'s study focused on experiments in the tropics, but its application to other climatic zones is still uncertain. Therefore, more experiments are needed when applying these prediction methods to other climate regions, which will help to improve the practicality of prediction models.

On the other hand, Palliwal et al. [56] provided a workable technique for determining appropriate agricultural placements in residential buildings. They used a 3D building model to estimate the DLI received by a residential building's vertical space, including external corridors, elevations, and windows. Shao et al. [97] developed a software application termed VFer, designed to model and predict the economic benefits and resource allocation within a variety of vertical farms. Predicting initial investment, return on investment (ROI),

plant yields, and the consumption of a wide variety of resources under various locations, types, sizes, and technological levels are some of the elements of VFer. The group also employed VFer to forecast the results of family vertical farming in Shanghai [75].

For environmental simulations, the Ladybug tool determines the amount of evapotranspiration using exclusively the albedo of plants and the green coverage, whereas ENVI-met simulations detail how plants interact with the outdoor microclimate [98]. In order to evaluate the visual, thermal, and energy performances of productive façades concerning the outdoor thermal environment of the Guangzhou residential community, Wang et al.'s study [82] devised a multi-objective analysis technique. To assess the energy and crop production performance of various design possibilities, various performance simulation programs were employed in the study, including Ladybug 0.0.67, OpenStudio, Daysim, EnergyPlus, and Radiance.

3.2. Technical Level Support

3.2.1. Plant Growth Environmental Conditions

Environmental elements, such as wind, water, temperature, and light, influence plant development. First, light is the primary factor that determines plant growth. It directly causes photosynthesis, which, in turn, influences plants' growth, morphology, and yield. Light requirements must be carefully evaluated in order to fit the unique conditions of a VFOF, as there may be variations in the amount of light present on a building façade [83]. A standard metric in agricultural activities, DLI is a measure of the total number of photosynthetically active photons received by a plant. It is essential for pinpointing the precise light conditions for a plant [83]. For instance, the ideal DLI for growing sweet basil is approximately 28.8 mol/m^2·day [99], while lettuce production typically requires a DLI of 12–13 mol/m^2·day or greater [89].

The design and implementation of an irrigation system must account for the unique water requirements of the plants and maintain ideal water conditions at the plant roots by precisely controlling the amount and timing of irrigation [43]. Different climatic conditions also have different requirements for irrigation systems. In hot and dry climates, evaporation is high, and irrigation frequency and water quantity need to be increased to ensure a water supply for plants. In wet or rainy climates, reducing irrigation frequency can avoid root diseases and resource waste. The LWS's structural panel design permits water to flow within the panels and facilitates easy-to-use watering techniques, like drip irrigation piping [43]. Using circular irrigation systems by LWS can improve efficiency by recycling drainage from the bottom of the living wall and recycling it [100]. Still, it can also lead to issues such as water quality management, energy consumption, and increased costs. Additional ways to enhance water use efficiency include graywater recycling [101], rainwater harvesting [102], and sensors that control water levels and watering times. Common crops such as cabbage, celery, and potatoes have a net daily irrigation requirement of 19 mm, 12 mm, and 28 mm, respectively [103]. Lettuce and cabbage have a similar net daily irrigation requirement. Particularly in summertime settings with high temperatures and intense solar radiation, adequate ventilation aids in plant transpiration, encouraging the plants to uptake more water and carbon dioxide [93].

It is crucial to select vegetables cultivated at the proper temperature because the local climate affects the façade's temperature. Indoor VF systems significantly increase crop output and quality by accurately controlling variables like temperature, light, water, humidity, and nutrients. This allows for many harvests throughout the year without being impacted by pests or the outside climate [104]. VF systems with artificial lighting systems significantly increase energy consumption, as electricity is required to provide light, maintain growth temperature, ventilation, and other environmental controls, which

directly affects operating costs [87]. New BIA solutions are made possible by the marriage of intelligent frameworks and the Internet of Things (IoT) [5]. These technologies, in the form of sensors and microcontrollers, can improve system efficiency and automate processes, which can contribute to the development of smart cities, environmental monitoring, and intelligent agriculture [105].

3.2.2. Medium and Cultivation Method

Soil has historically been the most often utilized substrate in UA [106]. But as technology has advanced, a number of substitute materials have been investigated, including rockwool, pumice, perlite, expanded clay, polyurethane foam, and coconut flour [107]. These soil-like growth substrates are necessary for plant growth.

Different plants could need different growing mediums in a particular UA system. To produce vegetables in a building corridor, Song et al. [48] employed a lightweight soilless medium made of coconut husk, commercial compost, and perlite. In a grow tank on the balcony of a high-rise apartment building, lettuce was grown using a lightweight soilless media made of perlite, commercial compost, and chicken manure. Waste coffee grounds were utilized as the growing medium for the flat mushroom culture. The growth and development of the plant's above-ground section were directly impacted by the substrate's capacity to hold onto water and nutrients. A study comparing the use of coco-gum and rockwool in VGS showed that coco-gum was better at promoting root growth, nutrient uptake, and gradual water release [108]. Compared to synthetic planting material, organic planting media keeps moisture longer and encourages root growth [109].

Indoor VFOF systems commonly use soilless techniques like hydroponics and aeroponics (see Figure 4). In a Shanghai residential building, Shao et al. [75] used soilless equipment to grow fruits and vegetables, examining the self-sufficiency of home-based VF. Hydroponics, a farming method that does not use soil, cultivates plants through nutrient solutions. This process saves a great deal of water and stimulates faster growth by eliminating the possibility of soil-borne diseases [27]. A form of the hydroponic system known as the nutrient film technique (NFT) suspends plants in a substrate like rock wool or sponge, with the roots of the plants submerged immediately in a nutrient solution [110]. Numerous studies have highlighted how hydroponic farms significantly boost their productivity. For instance, Barbosa et al. [111] discovered that lettuce yields in hydroponic farms were eleven times greater than those in conventional farming practices. Sathyanarayana et al. [112] further summarized that 23 crops were more productive in hydroponic systems than in soil tillage. However, hydroponics may also result in comparatively high energy consumption and waterborne disease [113].

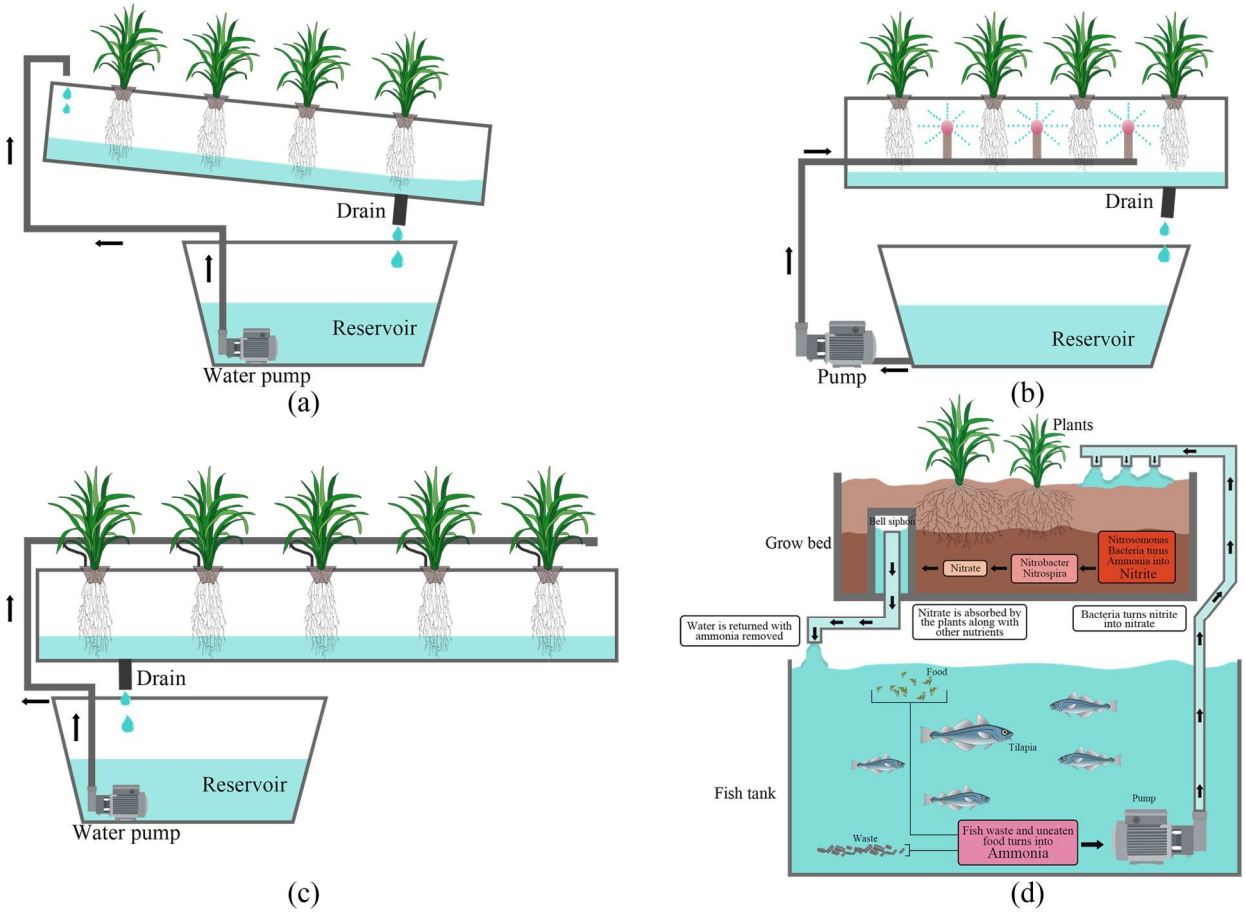


Figure 4. Soilless cultivation method: (**a**) nutrient film technique, (**b**) aeroponics, (**c**) hydroponics, (**d**) aquaponics. Adapted from [114,115].

Aeroponics is an additional soilless gardening technique that sprays the roots of the plants with nutrients and water. This technique is ideal for urban settings with limited water resources due to its 95% less water consumption than conventional agricultural practices and less than that required by hydroponics [59]. According to a study by Otazú [116], field production of crops like potatoes only uses from 1/10th to 1/30th of the water in an aeroponics system. This thin layer of water allows root oxidation and serves as a buffer for the plant. In addition, while eliminating soil-borne diseases, it also solves the problem of water-borne diseases that hydroponics still has the potential to solve. The initial costs of aeroponic systems are higher than those of hydroponic systems [117].

Hydroponic and aquaculture systems are combined in aquaponics [118]. This system's primary benefit is that it integrates crop and fish farming by exchanging nutrients through water that is used for both. Regarding soilless growing and effective water utilization, its benefits are comparable to those of hydroponic and aeroponic systems. Furthermore, it permits the simultaneous growth of fish and plants without requiring more water.

The use of soilless cultivation techniques in VFOF may limit its popularity due to its high cost. Simplifying the operation process of soilless cultivation technology, developing a more user-friendly system, and reducing the technical threshold and cost will promote its wide application. In horticultural activities, mixing can increase the fresh weight of individual plants, increase yields, and reduce agricultural inputs [119]. Some studies have shown that increased plant diversity may enhance productivity [120].

3.2.3. Supporting System

Vertical gardening on building façades can be achieved through various support structures such as scaffolding, rack systems, or railings. According to a recent study by Tablada and Kosorić [17], scaffolding or platform overhangs can be used to access façade planted gardening. On façades, experiments can be done with hydrophilic planting beds, vertical planting beds, and horizontal hydroponic pathways in addition to conventional planting beds. According to Basher et al. [47], edible climbing plants are guided upward by a rattan rack system in high-rise residential balconies. The plywood rack system is designed to hold the plants. Indirect VGS include support systems such as modular grids or stainless steel mesh to help plants grow upward by creating a second epidermal layer at a distance from the wall [84,121–123].

The VTN Architects-designed Urban Farming Office [124] has façade planters with various crops growing in them. The planter assembly consists of a basic reinforced concrete base structure and steel supports that hang the modular planters at various distances from one another based on how the planters react to yearly variations in the amount of daylight in the area.

On the other hand, Sky Greens' vertical farming system uses a novel rotating tiered planter [77] fixed to an aluminum A-shaped frame and can be adjusted to grow in either soil or hydroponics. This system's architecture increases agricultural productivity and quality by allowing plants to get consistent amounts of sunlight, water, and nutrients through various parts of the structure. Traditional support systems may lack structural strength, durability, and flexibility to meet the needs of different building types and façade characteristics. A number of studies have investigated the viability of employing composite materials as support systems. Particularly when cultivating halophytes or algae in salty conditions, these materials exhibit greater corrosion resistance than conventional metal supports [107]. Metal supports are less sustainable than cherry wood and HDPE [43]. Further optimization of the design and material selection of the support system is necessary.

3.3. Evaluation of Benefits

3.3.1. Planting Yield Benefit

This section brings together data from a range of critical studies, as seen in Table 7, that demonstrate the yield benefits of growing different crops and reflect the potential for self-sufficiency in diverse urban environments. The data are derived from experimental studies and numerical simulations in various regions and growing environments. From a multi-crop façade planting system in Singapore to a case study of family VF in Shanghai to a tropical climate adaptation study in Hanoi, Vietnam, and Singapore, these studies cover a wide range of crops from leafy vegetables to melons and fruits. These studies assessed crop yields and considered the self-sufficiency potential of VFOF and their adaptability to the environment. For example, a study in Singapore showed that up to 43% of leafy vegetable self-sufficiency could be achieved by planting on the façade of a building [48]. However, this outcome can vary according to latitude, façade orientation, and the sky view factor due to context. For higher latitudes on the north hemisphere, south façades receive higher values of sunlight [125], while near the Equator, east orientation with lower sky covering and north orientation assure the highest yields throughout the year and during the summer, respectively [126]. The outcome above underscores the potential of urban areas for food production, particularly in urban settings with restricted land availability. The Shanghai study, on the other hand, began at the household level and showed that a single household can significantly increase its food self-sufficiency with a family VF system, yielding about 24 kg/m^2 per unit area and an annual production of up to 112.55–147.39 kg [75]. In practical applications, the participation of residents is different, the laboratory cannot simulate the

actual home environment, and other factors will lead to the actual production being lower than the predicted value. Furthermore, Table 7 has also demonstrated how the growth environment affects production. With the right cropping system design, crops can reliably grow in tropical areas and adjust to hot, humid weather [48,54].

Table 7. A summary of some research on the planting yield benefit of VFOF (E: experimental; N: numerical simulation).

Year	Method	Crop	Type	Location	Main Output	Ref.
2022	E	Lettuce, Basil mustard, Okra, Coy sum, Water spinach, Cucumber, Bean, Bitter gourd, Sweet potato vine, Malabar spinach, Pumpkin, Oyster mushroom, Chinese spinach	Corridor, window, rooftop	Singapore	A self-sufficiency rate of 43% could be achieved using the façade planting system prototype; a self-sufficiency rate of 0.5% could be achieved using the prototype of the corridor planting system. Together with the rooftop cultivation prototype, the two could achieve a self-sufficiency rate of 46.4%.	[48]
2022	E+N	Buttered head lettuce, Pak-choi, Spinach, Iceberg lettuce, Strawberry	Window	Shanghai, China	From the perspective of a single household, the planting area that the planting system could provide was from 4.68 m^2 to 6.13 m^2. The annual output of vegetables and fruits was about 112.55 kg–147.39 kg, and the production per unit area was about 24 kg/m^2. The self-sufficiency rate of vegetables and fruits could be increased by a single family relying solely on the façade planting system, which was 15.79–20.68%. The simulation results show that the self-sufficiency rate of vegetables and fruits in the whole city could reach 2.54%, and the average was 2.15%.	[75]
2018	E	Pumpkin leaves, Corchurus Olitorius, Aloe Vera, Lantana Camara, Tropical Nettle	Wall	Lagos, Nigeria	The yield of the two prototypes is objective, which involves whether to provide dedicated maintenance. In the case of high maintenance, the prototype profitability took two years or more, while in the case of low maintenance, the prototype provided a relatively low yield level.	[23]
2021	E	Lettuce	Window & balcony	Singapore	East and north façades exhibit the most significant productivity, generating m and 828 g of lettuce, respectively. South and west façades yield 763 g and 550 g respectively. The amount produced represents 55–103% of the average leafy vegetable consumption of a 4-member household in Singapore (ca. 16 kg per year).	[126]
2024	N	Lettuce	Window & balcony	Singapore	The findings indicate that the upper part of the building could consistently satisfy the dietary requirements for leafy greens of a four-member household residing in a four-bedroom apartment in Singapore throughout nearly the entire year, whereas the middle sections could fulfill 89.1% of these needs.	[74]

Table 7. *Cont.*

Year	Method	Crop	Type	Location	Main Output	Ref.
2023	N	Sweet peppers, Tomatoes, Cucumber, Herbs, Lettuce, Microgreens	Façade, wall, window	Nablus, Palestine	In selected communities, planting systems on façades, walls, and windows could meet approximately 351%, 71%, and 25% of the local community's annual tomato consumption and approximately 237%, 44%, and 16% of cucumber consumption, respectively.	[79]
2016	N	Kang Kong, Water Mimosa, Chinese Celery, Water Cress, Pumpkin, Dragon Fruit, Banana	Balcony, traditional ground	Singapore and Hanoi, Vietnam	The index that has great influence on vegetable self-sufficiency rate is the volume ratio. When hybrid high-yield tillage was adopted, the precincts with the lowest plot ratio (PR < 1.9) achieved self-sufficiency.	[54]
2019	E	Winged Bean	Balcony	Penang, Malaysia	Wing beans can withstand the increase of heat from prolonged sunlight in high-rise conditions, and VGS installed on balconies can reduce indoor temperatures. However, the article did not mention the yield data of wing beans.	[47]

3.3.2. Energy-Saving Benefit

Solar radiation is one of the main factors affecting a building's interior and exterior environment [127]. By placing plants on the building's surface, VFOF can absorb and reflect solar radiation, significantly reducing the heat gain of the walls [61] and lowering the surface and ambient temperatures [128]. Table 8 summarizes recent studies on the aspects of VFOF that are energy-saving. It is important to emphasize that most energy efficiency research is related to VGS. As mentioned earlier, VFOF is a part of VGS, and VGS provides an important energy efficiency reference value for VFOF. However, due to the thin density and sparse distribution of the plant layer in VFOF, the shading effect on the back wall is small, so there may be significant differences in energy-saving benefits. Planting plants on the façades can be employed as a passive cooling technique to lower cooling energy consumption and increase occupant comfort [72]. In a study by Jenkins and Keeffe [81], DSF-integrated façade farms significantly reduced the building's energy consumption. It was reported in this study that typical DSF on office buildings used 36.3% less energy for heating, ventilation, and air conditioning (HVAC) than a standard single-layer curtain wall. With the integration of VF on the DSF, the energy usage further decreased by 44.4–48.5%. Furthermore, the HVAC energy usage might drop by 52.7–54.9% when the façade farm had large fish tanks.

The application of VFOF is especially critical in tropical climates. Basher et al. [47] implemented edible VGS on the balconies of a high-rise residential building in Penang, Malaysia. The results showed that the VGS stabilized the indoor dry-bulb temperature (DBT) and the mean radiant temperature (MRT) at 30.6 °C in the face of higher outdoor temperatures, reducing the building's cooling energy demand. Another study in New Cairo, Egypt, showed that LWS reduced energy consumption through planting boxes, enhanced thermal comfort, and reduced CO_2 emissions, which was more beneficial than other vertical greening systems [129]. Another way VFOF saves energy is by providing a better interior atmosphere. According to a study conducted in Nanjing, China, the CO_2 uptake rate of VF systems was 9.2 times higher than that of landscape plants that prefer shade [19]. Using a 100-plant-scale VF can lower indoor CO_2 content for a typical 30 m^2 office by 25.7–34.3%, which lowers building ventilation energy usage by 12.7–58.4%. In general, there are relatively few studies on energy-saving benefits led by VFOF at present,

and most of them focus on the analysis of individual cases. Lacking large-scale and systematic empirical studies, it is difficult to comprehensively evaluate its energy-saving potential under different building types and climate conditions. The future research should strengthen the in-depth discussion on the energy-saving benefits of VFOF.

Table 8. A summary of some research on energy-saving benefit of VFOF and VGS (E: experimental; N: numerical simulation).

Year	Type	Location	Method	Study Area	Finding	Ref.
2019	VGS	Penang, Malaysia	E	Residential building	When exposed to higher outdoor temperatures in the western direction, the indoor dry bulb temperature (DBT) and mean radiant temperature (MRT) behind the vegetated green screen managed to stabilize at a constant 30.6 °C, thereby reducing the energy required for cooling future buildings.	[47]
2021	VF	Nanjing, China	E+N	Office building	The CO_2 absorption rate of VF vegetables was 9.2 times higher than that of shade-loving landscape plants. For a standard 30 m^2 office accommodating 1–3 individuals, the use of 100 plant-scale VF could result in a reduction of indoor CO_2 concentration by 25.7–34.3%, leading to a decrease in building ventilation energy consumption by 12.7–58.4%.	[19]
2019	VF	Singapore	N	Residential building	The aspect ratio of vegetation significantly influenced the natural ventilation performance. When the aspect ratio was 0.5, meaning that vertical vegetation covered half of the area, the local wind speed could reach up to half of the inlet wind speed.	[76]
2022	VGS	Vienna, Austria	E	School building	The VGS reduced the façade temperature by a maximum of 11.6 °C.	[130]
2023	LWS	New Cairo, Egypt	N	Residential building	LWS with planter boxes reduced energy consumption, increased thermal comfort, reduced CO_2 emissions, and were more beneficial than other VGS. Buildings with living walls were 75% energy efficient.	[129]
2018	VGS	Guangzhou, China	E	Residential building	The study demonstrated the potential of green façades to save energy and improve the urban thermal environment. The shade air temperature of the green façade was reduced by 3.2 °C and 3.8 °C, respectively, at noon.	[131]
2021	LWS	Nanjing, China	E	Office building	In the case of the installation of LWS, the removal rate of CO_2 and PM2.5 was between 12% and 17% and 8% to 14%, respectively, and the relative humidity was slightly increased by 3.1–6.4%.	[132]
2016	VGS	Puigverd de Lleida, Spain	E	Two cubicles	Green walls and green façade (20–30 cm) provided 1 dB of sound insulation for traffic noise and between 2 dB (green walls) and 3 dB (green façades) for pink noise.	[133]
2019	VF	London, Britain	N	Office building	The double-skin façade (DSF) cut HVAC energy use by 36.3%. Adding a façade farm dropped it further to 44.4–48.5%. With a fish tank, the reduction peaked at 52.7–54.9%.	[81]

3.3.3. Benefits for the Environment

VFOF is an innovative urban food production and greening approach with numerous sound environmental effects. First, growing plants on building surfaces can further decrease carbon emissions, which can also greatly minimize the carbon footprint left by activities like vegetable transportation [134]. Plant transpiration not only lowers surface and air temperatures [128] but also efficiently moderates hot, dry weather in low-humidity settings. According to Daemei et al. [62], VGS can create a favorable microclimate by lowering summertime temperatures and raising wintertime ones. Furthermore, there is a significant chance that VGS will lessen the urban heat island effect (UHI) [128,135,136]. They may successfully lower city temperatures without consuming precious land resources because they are primarily used on the vertical surfaces of buildings [137]. A study by

Kim et al. [138] further supported the usefulness of VGS in enhancing outdoor thermal comfort, which found that urban canyons' maximum average radiation temperature could be considerably lowered. Moreover, VGS can lower particulate matter and stabilize humidity levels [139], which enhances the respiratory conditions of city people. It is worth noting that, due to the requirements of the VFOF, such as the plant spacing and crop growing cycle, the vegetable density is less than in the case of most VGS; therefore, it is expected that their environmental benefits are less significant than those of VGS.

3.3.4. Benefits to Society

As a reflection of the innate human need for nature, people have used and grown plants in buildings from ancient times to create a feeling of proximity to it [140]. It has been shown that being close to nature improves one's focus, creativity, and stability while lowering stress and fostering a positive sense of self-worth and self-perception [57]. It has also been discovered that having potted plants in offices and classrooms benefits people positively [141]. Furthermore, vegetation reduces glare, blocks sunlight, controls light intensity, and enhances visibility and safety [142].

Because urban settings are frequently small, it might be difficult for building owners and city inhabitants to locate areas with vegetation. Workloads and stressful work settings, however, can cause mental exhaustion and stress, and several studies have suggested that the mental health of those who live and work in cities may be declining [143]. It has been demonstrated that implementing VGS in cities enhances the well-being of urban dwellers [84,144–146]. According to a perceptual study conducted in Singapore, VGS significantly improved urban inhabitants' mental health [41]. Many people are drawn to cities by the possibility of better living conditions and employment prospects, which make urban regions seen as centers of opportunity. Urban greening, which includes VGS, can be seen as public art, and art thrives in urban settings [147], which may help to explain why VGS has taken on new life in numerous commercial locations. VGS revitalizes the city and enhances the visual quality [148]. One of the main advantages of VF is that it creates sustainable urban settings by supplying greenery and clean air, both of which have a beneficial psychological effect on people [149]. For urban dwellers, VF offers a picturesque experience, enhances leisure, and can raise social well-being and the standard of social life [150].

Additionally, health issues like weariness, cardiac problems, and hearing loss have been related to noise exposure [151]. Plants improve noise attenuation by absorbing, diffracting, and reflecting sound, as demonstrated by several earlier studies [152–156]. The air, plant, and soil in VF can all act as sound absorbers [60]. Other experiments conducted in the United States have shown that VGS absorb sound and reduce sound transmission [157]. This shows that by lowering long-term noise irritation, VFOF enhance people's subjective well-being.

3.3.5. Life-Cycle Assessment and Cost

Life-cycle assessment (LCA) is a standardized scientific method widely used to assess the environmental impacts of products throughout their life cycle. The use of LCA is critical in the context of the rapid development of VFOF, as it encompasses all stages from raw material procurement to manufacture, usage, and final disposal [43]. According to energy assessments, VGS exhibits overall sustainability in retrofit projects [158]. However, the particular materials, plant species, maintenance, and irrigation requirements further hampered VGS's sustainability [145].

According to Natarajan et al.'s [109] analysis of LWS's energy, water, and greenhouse gas emissions through all life-cycle stages, the utilization stage had the greatest effect on the

overall burden. Through a monitoring campaign conducted at the VGS, Perini et al. [159] quantified the water–energy–climate nexus of a VGS in Italy using the LCA methodology. They discovered that, despite a 42% increase in the Water Scarcity Index (WSI) during the utilization phase, the Global Warming Potential (GWP) and the environmental impacts of energy consumption generated by the VGS scenario were reduced by 56% in the VGS scenario compared to the baseline scenario. According to a comparable life-cycle study carried out in a continental Mediterranean climate by Chàfer et al. [160], VGS contributes up to 90% of the overall environmental impact during the operational phase, when it has the most environmental impact. Nonetheless, using VGS can lessen the environmental burden by roughly 50%, particularly in the summer. In their study done in Singapore, Song et al. [161] used system dynamics (SD) modeling and LCA to perform a thorough comparative analysis of several cultivation methods. The study made clear that while indoor farming systems require less land overall, their increased energy consumption may impact the sustainability of the ecosystem as a whole. On the other hand, naturally lit vertical farm (Vnat) systems use natural light instead of artificial lighting, which lowers energy usage and related environmental effects. A Swedish urban vertical hydroponics system's environmental assessment [162] revealed that factors like growing media, pots, electricity consumption, raw material transportation, and product delivery can all be identified as impacting the environment by assessing the system's environmental performance and contrasting possible improvement options. Research has demonstrated that using pulp pots instead of plastic pots can significantly reduce greenhouse gas emissions, the effects of acidification, and the depletion of abiotic resources.

Life-cycle costing (LCC) considers all of a system's or product's costs throughout its life, including the original outlay, ongoing maintenance, and disposal expenses [163]. Huang et al. [164] created a LCC framework that incorporates the different phases of VGS's life cycle and its impact on building energy efficiency to assess the technology's financial viability. The study's findings demonstrated that, during the VGS's life cycle, the operation and maintenance phase incurred the most significant percentage of expenditures (73.7–83.9%). Eventually, a prediction model was created to assess VGS's LCC and give VGS enterprises a foundation to make offers [165]. Furthermore, Huang et al. [164] offered several suggestions for cutting the cost of VGS, such as choosing the right kind of VGS, plants, and support structures; optimizing the design and installation; creating a successful operation and maintenance schedule; and utilizing the many advantages of VGS to raise the cost–benefit ratio. Furthermore, Wu et al. [166] employed a Cost–Benefit Analysis (CBA) to assess the viability of implementing VGS in Singapore's commercial complexes. The study shows that the implementation of VGS in commercial complexes is a feasible investment with good economic return value. Studies involving VGS and VF provide a reference perspective for VFOF. Since the technologies and types of VFOF are uneven, low-technology strategies consume less energy than high-technology strategies, and their impact on the environment is also different. Therefore, LCA studies on different VFOF should be strengthened in the future to provide more comprehensive data support.

3.4. Promotion, Legal Framework, and Acceptance of VFOF

3.4.1. Role of Government and Other Agencies

VFOF has been promoted from governmental, private, and community bodies. Government plays a crucial role in promoting VFOF as one type of UA's legitimacy, and significance have been established by numerous governments, especially after 1992 when the United Nations Development Program's (UNDP) Urban Agriculture Advisory Committee (UAAC) accepted the recommendations of the Support Group for Urban Agriculture (SGUA) [167]. Acting as policymakers, many governments have included UA in their

national legal frameworks. Governments have also increased UA's economic appeal by offering incentives [168]. This is the case of the Singaporean government, which provided vegetable seeds to households as an incentive for home gardening to improve food security and the food system's resilience [169]. The funding of VF technology development and research is another way the government performs a role. According to a study by Specht et al. [18], financial support and policy recommendations can help the government advance research and development of VF technologies. This covers elements that can enhance the effectiveness and sustainability of VF, such as innovative cultivating methods, energy use, and resource recycling. Developing and utilizing analytical models to identify appropriate design and technological approaches can enhance the integration of indoor gardening into architectural space [170].

The government must consider and encourage the development of agriculture in urban high-rise buildings by incorporating it into planning and building rules, as highlighted by Despommier's vertical farm proposal [171]. Governments can encourage VF by providing direct cash incentives, tax exemptions, or concessions on land utilization. To raise public awareness and acceptance of VF, public outreach, and education are essential. To encourage the widespread use of VF, the government can educate the public about its benefits to the environment and the economy by organizing educational events and community outreach programs [48]. Furthermore, a survey of residents in the Athens metropolitan region using questionnaires found that while residents had positive sentiments toward vertical gardening at home, they might not have the essential information or mindset [172]. This implies that there is a lot of space for improvement regarding to government understanding, education, and policy subsidy provision.

Private interest in VFOF is also gaining momentum. They see many benefits and potential in VFOF. This interest is not only reflected in the R&D investment in VFOF technology but also in the actual financial support for related projects. Moreover, partnerships between governments and the private sector are becoming more common. Through the public–private partnership model, the policy support of the government and the operational efficiency of the private sector can be combined to promote the successful implementation of VFOF. This cooperative approach has already been applied in some cities and has achieved remarkable results [173]. In addition, some academic research is also funded by private companies.

NGOs actively contribute to the development of UA and VFOF through specific projects. Freight Farms has successfully implemented container farms in multiple geographies, facilitating the adoption of UA in the non-profit, healthcare, and education sectors [174]. Upfarming's projects not only focus on environmental sustainability but also emphasize community engagement and education so that people can see and participate in the food production process at their doorstep [175].

3.4.2. Social Acceptance

The promotion of VF largely depends on community acceptance, which is impacted by sharing costs and benefits as well as by those participating in the decision-making process [176]. Deeper public involvement in food production not only enhances the sense of belonging, but also inspires active participation, which helps to increase public interest in new agricultural activities in cities [177]. It is estimated that 25–30% of urban dwellers engage in UA globally [178]. Sustaining livelihoods through subsistence UA is essential, especially for low-income nations in the global South [178]. And in northern cities, there is a renewed interest in growing their fruits and vegetables, whether by individuals, families, or community groups. According to the "Garden to Table Report" published by The National Gardening Association (NGA) [179], 35% of Americans grow some of their food, which

is the most significant percentage of involvement in over a decade. The fastest rise was observed among urban populations and individuals between 18 and 34. Growing America: The Story of the White House Garden and Gardens Across America, written by Michelle Obama and published in 2012, might have added to the appeal of backyard and community gardens [179]. Allotment plots, used to grow food, have become increasingly popular in the UK in recent years [96]. The health and social advantages of UA, particularly fruit and vegetable gardening, are becoming more widely acknowledged by people living in the Global North [180–185].

Several studies have shown that social acceptance is a critical factor in the success of urban and vertical farming programs [168,186,187]. In Singapore, Kosorić et al. [188] surveyed home-based farming on building façades among public housing residents. The findings indicated that the implemented concepts were highly compatible with the requirements of public housing inhabitants, and the majority of survey participants expressed a readiness to participate in outdoor gardening pursuits, with a particular inclination toward smaller vertical farms. Residents also preferred to garden closer to their apartments, which allowed them to interact with their neighbors and may have also been preferred due to better safety, accessibility, and hygiene properties [188]. The most pressing issues, however, were cost and safety. Through an online survey, Shao et al. [189] investigated public approval and desire for VF in urban residential structures. They discovered that 83.8% of respondents were eager to adopt the practice and that VF could be used for food production an average of 81.4% of the year. According to a Tafahomi et al. [190] survey of city dwellers in Rwanda, most respondents thought vertical gardens were more advantageous and had a favorable attitude toward them; however, they were more worried about the system's cost and maintenance. In the research by Tablada et al. [32], specialists and authorities in the fields of horticulture, agronomy, solar systems, and architecture took part and offered favorable feedback. However, those experts related to architectural design expressed concern about the aesthetical integration of the solar and farming systems on the façades. VF is becoming increasingly accepted in society, and this trend is predicted to continue after the pertinent problems are resolved.

3.5. Safety Concerns

3.5.1. Trace Contaminants Enter the Food Chain

Contaminated urban horticultural products could be dangerous for people's health. Research has indicated that eating crops from contaminated locations in developed as well as developing nations can expose people to trace metals in their food, which can result in significant health issues for the public [191–194]. A study by Säumel et al. [195] further confirmed the importance of air deposition in contaminating vegetables grown in urban neighborhoods, especially leafy vegetables, which are more likely to accumulate air pollutants [196]. This could result in the buildup of contaminants in crops due to the comparatively high levels of air pollution in cities [197], which could have detrimental effects on public health [198]. Since most residential areas are near roads, the buildup of pollutants in this area is a significant problem.

Furthermore, harmful tire dust produced by rapid automobiles may be exposed to unprotected crops near highways. This highlights how crucial it is to thoroughly wash vegetable leaves to remove all particles before selling or consuming them [199]. Increased traffic loads heighten trace metal levels in crop biomass. However, these levels can be considerably decreased by erecting a barrier between the growing site and the road [195]. Koski's [199] study found that vegetable leaves do not absorb airborne heavy metals and particulates, which offers a glimmer of hope in reducing the levels of heavy metals in

vegetables. To reduce the amount of heavy metals in vegetables, it is imperative to employ low-heavy-metal growing media [200].

3.5.2. High-Altitude Safety Problem

Vegetables or containers can become so-called "killer trash", endangering the lives of onlookers below, if they are located beyond the building envelope and are not securely fastened to the system [201]. This problem must not be overlooked. It highlights how crucial it is to take plant fixation and support structure safety and dependability into account when developing VFOF systems. Consequently, experts advise using indoor systems behind glass curtain walls in high-rise structures to minimize the risk of working at heights while still providing appropriate protection for the plants from the severe exterior climate [17]. There may be flexibility in selecting indoor or outdoor VF systems for low-rise and mid-rise buildings. To guarantee operator safety during agricultural tasks like replacing substrate, planting, and harvesting, it is crucial to establish an automated irrigation system and add fixed or moveable access structures for outdoor systems [17]. Additionally, the integration of VFOF systems must comply with the building's fire safety codes, which can impose restrictions on the materials used and the layout of the farming systems. These codes are essential to prevent potential fire hazards and ensure the safety of the occupants and the structure itself. In a survey conducted in Singapore, experts made a series of recommendations aimed at improving the design and accessibility of productive façade prototypes integrated with solar panels, such as the use of safety grills in balconies and open corridors [32]. These steps facilitate maintenance while also increasing operating safety. Additionally, in order to integrate plants, irrigation, and maintenance systems as efficiently as possible, VF techniques on the façade necessitate an evolution of the building envelope design. This gives the building economic and social value in addition to aesthetic and environmental value [17].

3.6. Example of Implementing VFOF

Table 9 shows a selection of projects that have recently applied VFOF. The list includes both real projects and conceptual ideas. This section provides a brief explanation of several real projects and conceptual ideas from more recent years. Home-based VFOF has become popular in urban areas as façade farming technologies advance, frequently taking the shape of simple installations on balconies or open hallways. These systems are becoming increasingly popular because they are simple to maintain and install and need no expertise from the farmer. Growing flexible fruits, herbs, and green vegetables is essential for open-air VFOF since it guarantees a consistent crop yield and increases the potential for UA to be self-sufficient [17]. More sophisticated VF systems, such as CEA, create particular environmental conditions according to the more rigorous selection of crops. The creation of CEA VF systems offers a new approach to food production for cities by overcoming the seasonal and geographic limitations of traditional agriculture. Apart from sophisticated VF systems, alternative inventive approaches exist in agriculture. By carefully regulating environmental variables, these systems increase agricultural yields and quality and allow for year-round production cycles. Notwithstanding the obstacles posed by energy consumption and maintenance, they offer a wide range of crops; satisfy consumer demand for locally grown, fresh food; and create new opportunities for sustainable UA.

In Singapore, Netatech launched the Vertical Food Stage project [173], which uses residential public housing areas' façades for VF. Crops were grown in a pesticide-free environment thanks to cloud computing, solar drip irrigation, and rainwater collection. The concept connects growers and buyers directly through an online marketplace to supply

fresh, locally grown vegetables while drastically lowering its carbon footprint. To diversify Singapore's food supply, Netatech also intends to produce rice inside a Vertical Food Stage.

To grow vegetables on a vertical curtain wall façade, an interdisciplinary team led by Bright Farm Systems created the Vertically Integrated Greenhouse (VIG) [202], a highly productive, lightweight, modular, climatically responsive vegetable culture system made up of several horizontal hydroponic trays (2 m in length) suspended from a factory cable hoisting system that is connected to a computer-controlled motor for rotation. Depending on the crop cycle, the entire voyage begins at the bottom when the seeds sprout and continue along the wall until the ultimate harvest, typically in 30 days. In addition to serving as curtains or shade mechanisms, the trays allow light into the interior. The design has been introduced in various proposals around the world.

Matharu designed VF prototypes for high-rise façade planting [78]. They adapted to the needs of residential, office and retail spaces while also responding to the terrain and climate of Auckland. The prototypes showed how to properly integrate the VF system with the building fabric, window openings, and other systems. However, further studies are needed on different issues about the logistics of the planting, harvesting, marketing, and waste disposal procedures, as well as how these activities relate to commercial, residential, and office activities before the suggested system can be put into practice on a high-rise building.

Another intelligent way to produce food in urban areas is identifying and using wasted urban space in residential districts. With just 35 square meters of space needed, the GreenBelly system designed by AVL Studio is a creative modular system that can produce over 6400 kg of veggies annually [203]. This approach has a good influence on social sustainability by raising community understanding of agricultural practices and healthy eating through education and giving low-income families access to organic, reasonably priced vegetables. Additionally, the use of recycled materials and organic waste in the GreenBelly system further contributes to its environmental sustainability.

An aquaponics prototype created by Jenkins et al. [204] and Jenkins [205] was incorporated into the building's façade. Two layers of NFT-based soilless growth channels and a fish tank were set up in a full-size test bed within the DSF's interior, which was once an abandoned factory near Salford, UK. Several simulations were conducted to verify that every channel in the prototype received enough sunshine and to evaluate the façade system's reduction in heat transmission. The test bed needed to be tested on a natural building façade because it had to be installed inside. Potential water intrusion and the system's unproven advantages were among the technical and societal issues noted. Including expenditures and Manchester food prices, the complete façade system's payback period was projected to be 7.5 years.

Farming Architects [73] used a similar method to build a system that was installed on multiple balconies in Hanoi and other Vietnamese cities. Although the system was first created for aesthetics, it may also be used to grow edible fish, veggies, and herbs. Many plants were arranged on a steel grid to provide shade and shelter from heavy rains, allowing for various layouts and control over daylighting. The project utilized materials widely used in Vietnam, making it scalable and flexible for replication and promotion in different locations.

Table 9. Implementation cases and conceptual cases of VFOF.

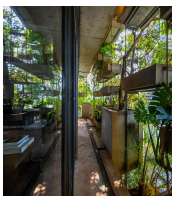
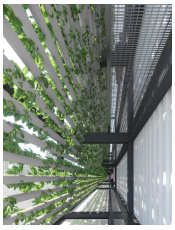
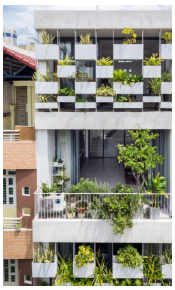
Picture	Name	Year	Location	Type	Building Type	Area	Ref.
	VTN Architects' Urban Farming Office	2022	Ho Chi Minh City, Vietnam	Façade	Office Building	1386 m^2	[206]
	Vertical Food Stage	2021	Tampines, Singapore	Wall	Residential building	146 buildings	[173]
	Urban ecological balcony renovation	2018	Hanoi, Vietnam	Balcony	Residential building	35 m^2	[207]
	Modular Aquaphonics	2018	Britain	Façade	Large building	Unknown	[208]
	Productive Façades at NUS-CDL T2 Lab	2018	Singapore	Window & balcony	Residential building	60 m^2	[31,32]
	GreenBelly	2018	Spain	Scaffold	Building	35 m^2	[203]
	SR-1 House	2017	Ho Chi Minh City, Vietnam	Balcony	Private residence	162 m^2	[209]

Table 9. *Cont.*

Picture	Name	Year	Location	Type	Building Type	Area	Ref.
	House in Yatomigaoka	2015	Aichi Prefecture, Japan	Façade	Private residence	280 m^2	[210]
	Green sandwich House	2012	Saigon, Vietnam	Façade	Private residence	300 m^2	[211]
	The 2020 tower	2007	New York, America	Double skin	Tower	621,000 m^2	[212]

4. Discussion

The most recent developments in VFOF research are compiled in this paper. The key messages of this paper are as follows:

Food systems are under tremendous strain as the world's population continues to rise and is predicted to reach nine billion people within the next 20 years. Due to the expanding size of cities and the increasing distance between food production and consumption, the infrastructure needed for transporting and distributing food is expanding. This globalized food system is responsible for 29% of the global greenhouse gas emissions [7]. Through the efficient use of vertical space in urban buildings, VFOF, a new UA concept, can significantly improve urban food self-sufficiency, raise the ecological resilience of cities, reduce carbon emissions, and improve the quality of life for residents. Planting on building façades can lead to a very considerable self-sufficiency rate, according to a Singapore study [48]. The application of low-technology cultivation strategies is beneficial in reducing food miles and carbon footprint [161]. Another study [19] in Nanjing, China, showed that a standard 30 m^2 office using VF systems reduced building ventilation energy consumption by between 12.7% and 58.4%. Plants on the façade can lower the surrounding temperature by shading and crop evapotranspiration, lowering building energy use and enhancing thermal comfort. By reducing the urban heat island effect and improving air quality, VFOF can benefit the urban environment.

Architectural beauty, structural safety, plant growth requirements, and maintenance viability are all critical considerations in the design of VFOF. To achieve the best possible integration of agricultural output and architectural aesthetics, different façade types have varied design requirements that must consider a variety of façade characteristics, such as windows, balconies, DSF, and exposed walls. The viability of food production is increased when system components are designed properly, enhancing the efficiency of space usage. It should be emphasized that VFOF operates year-round in warm climates, but in cold climates, where plant growth is limited, additional insulation measures may be required.

The selection of plant species, the growing media, the irrigation system, and the potential effects of plant development on the building structure must all be considered in the design. These elements determine the system's feasibility, sustainability, and environmental adaptability. Furthermore, the development of Internet of Things (IoT) technology will probably increase VFOF's production potential [5].

Even though there is an increasing public interest in VFOF, outreach and education initiatives are still needed to raise knowledge and engagement. Furthermore, worries about cost and safety are thought to be the most urgent. On the cost side, VFOF uses low-tech strategies, such as simple plant boxes and manual irrigation systems in home balconies or corridors, to reduce costs. However, when governments or institutions scale up, more systematic solutions may be adopted, such as the installation of complex irrigation and environmental control systems on large building façades. While this improves production efficiency and crop quality, it also increases initial investment and operating costs. Policies, rules, and fire safety specifications could also restrict the use of VFOF. Consequently, the government's participation is critical and should include creating supportive regulations, offering financial incentives, and considering the integration of VFOF in urban planning. It is worthwhile to consider recognizing VFOF as one of the urban development strategies used globally and creating government regulations to improve the economic profitability and market accessibility of vertical farm products. In addition, the involvement of the private sector and communities can also make a big difference. Even though VFOF has much to offer regarding social and environmental benefits, more research will be required to determine how cost-effective it is. Important instruments for evaluating the effects of VFOF on the environment and its economic feasibility are LCA and LCC. Future research must consider the impact of VFOF from the perspectives of the environment, economy, and society—the three key elements of sustainability.

There are few studies on VFOF, which restricts its widespread societal acceptability. After analyzing the existing literature, this paper finds that the choice of implementing a VFOF can be divided into six stages (Figure 5). It offers a comprehensive implementation blueprint in the event that VFOF is chosen. The process involves social, economic, and environmental aspects in addition to technical considerations. It is designed to help stakeholders better understand and manage the process. Although the concept of VFOF is gradually gaining popularity, many imperfections remain. Therefore, further exploring the optimal design and research of VFOF is necessary to adapt to the diversified built environment and various needs. In addition, interdisciplinary collaboration is needed to integrate expertise in materials science, architecture, horticulture, and environmental engineering to enhance the overall performance and sustainability of the system. Finally, considering the potential contribution of VFOF to reducing urban carbon footprint and promoting carbon neutrality, the economic feasibility and social impact of VFOF in different urban settings need to be assessed to provide a scientific basis for policy formulation and urban compatibility.

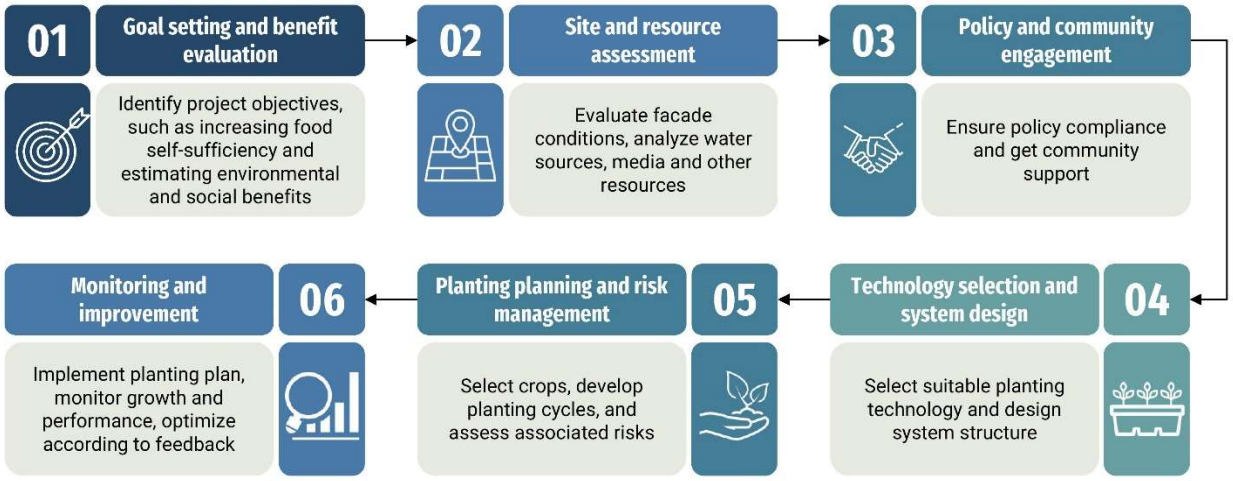


Figure 5. Proposed phases for the implementation of VFOF. Source: the authors.

5. Conclusions

In summary, this study aims to provide an overview of recent research advances in VFOF, covering several dimensions such as design, technology, societal aspects, and environmental benefits. The review, based on 166 journal articles covering key sub-themes described in detail, has revealed that VFOF is a promising strategy to improve urban food self-sufficiency, optimize building thermal performance, promote energy conservation and emission reduction, and enhance the standard of living for locals. Enabling crop production in building façades not only makes efficient use of normally unproductive urban surfaces but also provides a fresh, localized source of food for urban residents. In particular, VFOF also helps to reduce carbon emissions associated with food transportation while absorbing carbon dioxide through photosynthesis, providing a carbon sink for cities. This practice can contribute to the goal of carbon neutrality in buildings and cities.

However, there are challenges in putting the technology into practice. The promotion of VFOF still needs to cope with several significant obstacles, including a high initial investment, operating costs, technological complexity, legislation and regulatory restrictions, and public acceptance. The choice of the appropriate VFOF type and technology for the implementers under different conditions is critical for cost control and return efficiency. The government can reduce the economic burden of enterprises and individuals in VFOF projects by providing policy support such as financial subsidies and tax incentives. Strengthening research and innovation in VFOF systems to develop more cost-effective planting systems can also reduce costs and improve efficiency. Furthermore, during design and implementation, consideration must be given to the safety of VFOF systems, the selection of plant growth conditions, and the potential effects of plants on the building fabric. Government policy backing and public education play critical roles in increasing the social acceptance of VFOF. The success of VF initiatives depends heavily on public participation, and people are more likely to participate in horticultural activities near their homes.

In order to promote the better development of VFOF, future research must focus on improving the sustainability and adaptability of VFOF design, including the adaptability of different building types and environments, the degree of humanization and performance of the system, cost, and environmental benefit assessment. Meanwhile, evaluating their social and economic effects is essential for creating policies and promoting technology.

In summary, the study's conclusion emphasizes the potential advantages of using VFOF to increase urban food production and cities' ecological resilience. It is intended that providing an important reference and guidance for relevant researchers and their interested

individuals, policymakers, and others will stimulate additional study to maximize its benefits and minimize any drawbacks.

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Abbreviations

BIA	Building-Integrated Agriculture
BIPV	Building-Integrated Photovoltaic
CBA	Cost-Benefit Analysis
CEA	Controlled Environment Agriculture
DLI	Daylight integral
DSF	Double-skin façades
GF	Green façades
LCA	Life-cycle assessment
LCC	Life-cycle cost
LWS	Living wall systems
NFT	Nutrient film technique
UA	Urban agriculture
VFOF	Vertical farming on façades
VF	Vertical farming
VGS	Vertical greening systems

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