buildings

Article

The Influence of Vertical Greening Systems on Building Energy Consumption and Comprehensive Carbon Emission

Hongtu Mi [1], Shidong Wang [1], Tingting Wang [2] and Tao Li [3,*]

[1] Gansu Institute of Architectural Design and Research Co., Ltd., Lanzhou 730000, China; mihongtu63@163.com (H.M.); wangshidongwust@gmail.com (S.W.)
[2] School of Civil and Architectural Engineering, Zhengzhou University of Science and Technology, Zhengzhou 450065, China; tinger@zit.edu.cn
[3] School of Urban Construction, Wuhan University of Science and Technology, Wuhan 430065, China
* Correspondence: litao1001@wust.edu.cn

Abstract: Vertical greening systems, in addition to enhancing the aesthetic design of building facades, contribute to energy saving and carbon reduction. This study proposes a simplified calculation method for the annual comprehensive carbon reduction potential of vertical greening systems, considering both indirect carbon reduction and direct carbon sequestration. The annual energy-saving potential of vertical greening systems was numerically simulated using EnergyPlus 9.2.0 for a typical three-story office building in four cities in different climate zones: Xi'an, Shanghai, Guangzhou, and Kunming. The potential of indirect carbon reduction and that of direct carbon sequestration of the building for a full year as a result of the vertical greening system in these areas were calculated. The results show that vertical greening systems using Virginia creeper reduced annual building energy consumption by 1.2%, 3.1%, 8.7%, and 4.0% in Xi'an, Shanghai, Guangzhou, and Kunming, respectively. The impact was most significant in Guangzhou, where the air condition period was the longest. When the leaf area index is 3, the indirect carbon reduction in Guangzhou can reach 1105.45 kgCO_2/a. In regions with higher summer air conditioning energy consumption, the vertical greening system exhibits better indirect carbon reduction potential. In Kunming and Guangzhou, where the growing season for creeper is longer, the system shows higher total annual carbon sequestration. In Guangzhou, the vertical greening system has the highest overall carbon reduction potential. The vertical greening system provides significant carbon reduction benefits across all climate zones and can strongly support the building industry's efforts to achieve carbon neutrality.

Keywords: building facade; vertical greening system; energy consumption; carbon emission

Academic Editor: Rafik Belarbi

Received: 27 December 2024
Revised: 23 January 2025
Accepted: 25 January 2025
Published: 3 February 2025

Citation: Mi, H.; Wang, S.; Wang, T.; Li, T. The Influence of Vertical Greening Systems on Building Energy Consumption and Comprehensive Carbon Emission. *Buildings* **2025**, *15*, 471. https://doi.org/10.3390/buildings15030471

1. Introduction

With the intensification of urbanization in China, the urban population is growing rapidly, leading to a significant increase in urban building energy consumption [1]. Carbon emissions during the operational phase of buildings dominate the construction industry, with emissions reaching 2.21 billion tons in 2018, accounting for 21.7% of the country's total emissions [2]. Therefore, exploring various strategies for buildings [3,4] can help reduce building energy consumption and carbon emissions, contributing to the achievement of carbon neutrality. Among these strategies, building greening is one of the effective means to reduce carbon emissions. By integrating buildings and greenery, vertical greening on building facades can enhance architectural aesthetics and mitigate the negative impacts of buildings.

It is well known that building vertical greening can effectively alleviate environmental issues such as air pollution, the urban heat island effect, and noise, while also optimizing the thermal performance of the building envelope and significantly reducing building energy consumption. Vertical greening has a long history and is at the forefront internationally. Many countries have introduced a series of regulations and policies to encourage vertical greening, leading to its development. A number of developed countries have made substantial investments in vertical greening, resulting in many outstanding examples [5,6].

Many studies have shown that adding vertical greening systems can bring some good effects to buildings [7]. In particular, it provides a significant cooling effect on exterior walls during the summer, improving physical thermal comfort [8,9] and psychological thermal comfort [10,11], and enhancing occupants' overall thermal comfort [12,13]. Susorova et al. [14] conducted experiments on four orientations of existing university buildings in Chicago, USA, comparing exposed facades with ivy-covered ones. They found that the ivy-covered facades reduced surface temperatures by up to 12.6 °C. Liu et al. [15] performed continuous field tests on rooms with and without vertical greening on west-facing walls. They found that the room with vertical greening had an average air temperature of 1.8 °C lower than the room without it, significantly improving the indoor thermal environment. Morakinyo et al. [16] used the validated ENVI-met model to study the impact of urban density on coastal greening's cooling potential in Hong Kong. They concluded that 30–50% of the facade area needed to be greened to reduce both daytime and nighttime air temperatures by 1 °C. This also helped improve pedestrians' thermal comfort during the day by at least one thermal comfort level.

In addition, vertical greening can reduce the energy consumption of building HVAC systems [17,18], lowering carbon emissions during the building's operational phase. Li et al. [19] simulated the energy-saving effects of horizontal (roof greening) and vertical greening in Ningbo using DesignBuilder. The results showed that certain combinations of horizontal and vertical greening could reduce cooling loads by 8.8% and heating loads by 1.85%. Zhang et al. [20] proposed a method to simulate vertical greening using EnergyPlus combined with additional heat source terms and an energy management system. Their simulations in four typical cities in China's hot summer and cold winter regions showed that vertical greening reduced cooling loads by 11.7–18.4%. Karimi et al. [21] designed a building on a university campus in temperate and humid areas. They simulated the energy-saving effects of two methods using three different plant species to construct green walls. Their study found that increased leaf density could reduce building energy consumption. This shows that even for vertical greening, selecting the right plant species and construction methods is essential. In any case, vertical greening reduces building energy consumption, especially cooling loads during the summer, with up to 20% reduction [22–24].

In addition, vertical greening plants themselves have carbon sequestration abilities, which can offset carbon emissions during the building's operational phase [25–27]. The main variables affecting the carbon sequestration capacity of plants are their species [28] and leaf area index (LAI) [29]. Charoenkit et al. [30] compared the cooling effects and carbon storage abilities of three types of vertical greening plants. They found that Cuphea hyssopifola, which has the densest leaves, smallest leaf size, and woody stems, performed the best in both aspects. Gratani et al. [31] found that plants with a high LAI were efficient at sequestering CO_2. However, some plants with smaller leaf areas could achieve the same photosynthetic rate as broader-leaf plants by having a larger number of leaves. Thus, selecting plant species with high carbon sequestration potential is a key research focus.

In summary, the existing vertical greening research often separates the carbon emission reduction of building energy conservation from the carbon sequestration of plants. However, studies that combine these two aspects to assess the overall impact of vertical greening on carbon emissions are temporarily lacking. This is especially true for improving the vertical greening design of building facades from a carbon emission perspective. Although Yang et al. [32] quantified the total CO_2 reduction of newly built intensive green roofs through one year of carbon flux observation and building energy simulations, there is still a lack of analysis on the comprehensive carbon reduction potential of vertical greening systems.

Based on existing research, seen in Figure 1, this study proposes a simplified calculation method for the comprehensive carbon reduction potential of vertical greening systems. It analyzes the impact of different LAI conditions on building carbon emissions. Section 2 presents a theoretical analysis and establishes models for energy-saving indirect carbon reduction potential, photosynthetic direct carbon sequestration potential, and comprehensive carbon reduction potential. Section 3 includes a case study, with numerical simulations for four typical cities. It outlines the physical model of the typical building, the vertical greening system, the HVAC system, and the settings for the numerical simulation's meteorological parameters. Section 4 presents the results and analysis of energy-saving potential, indirect carbon reduction, direct carbon sequestration, and comprehensive carbon reduction for the vertical greening system in Xi'an, Shanghai, Guangzhou, and Kunming under different LAI conditions. The section also discusses the limitations of the current study and future research directions.

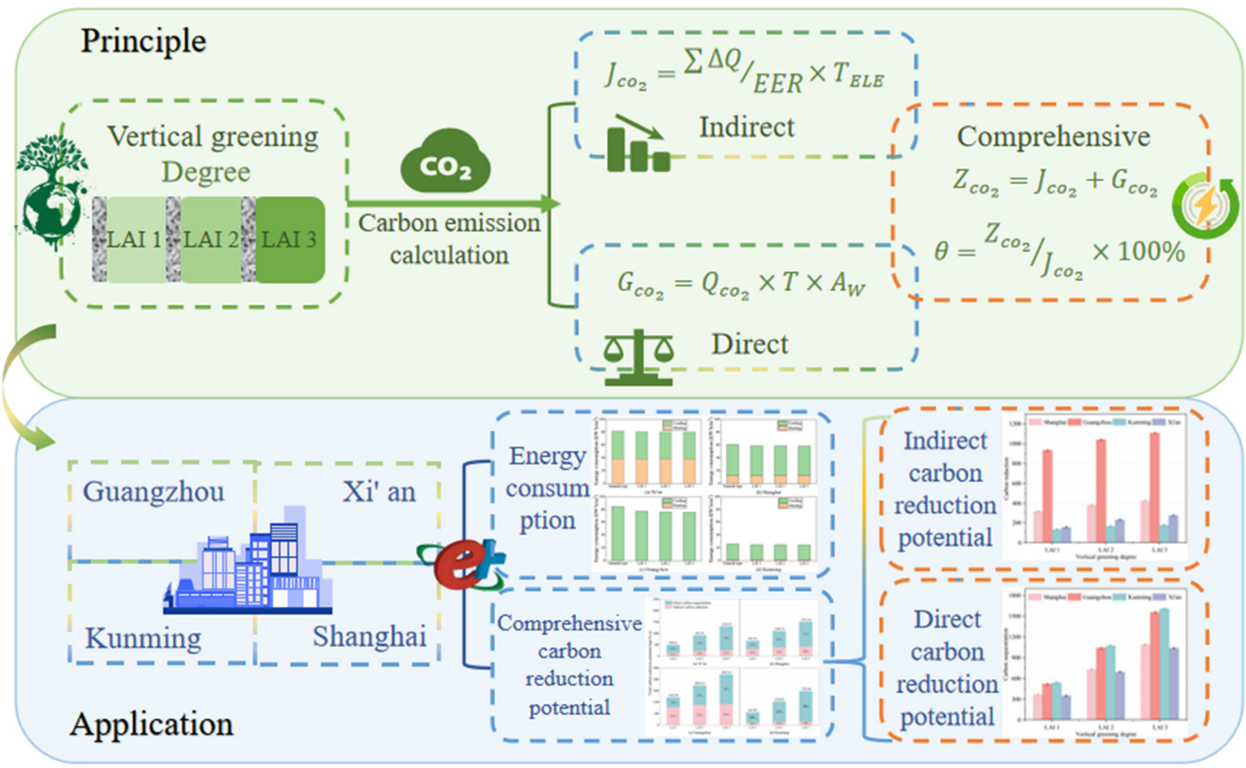


Figure 1. Thesis research frame diagram.

2. Methods

Vertical greening reduces carbon emissions during a building's operational phase through both direct and indirect effects. First, vertical greening can reduce solar radiation heat gain on walls by providing shading. Additionally, it changes the building's thermal parameters and, through transpiration, reduces heat transfer to the interior. This helps lower the energy consumption of the building's HVAC system. A reduction in operational energy consumption directly leads to a decrease in carbon emissions during the building's operational phase. Secondly, many vertical greening plants are climbing species. These plants have characteristics such as high leaf density and extensive coverage, making them highly effective at sequestering carbon. This carbon sequestration can offset the indirect reduction in carbon emissions caused by energy savings in the building's operation.

2.1. Calculation of Indirect Carbon Reduction Potential

The operational energy consumption of a building is primarily due to the HVAC system. This includes heating and cooling loads from the building envelope, solar radiation heat gain, fresh air ventilation load, as well as internal heat gains from occupants and equipment. Among these, heat transfer through the external wall (Q_w) is a significant component of the building envelope heat load. It can be expressed as the product of the thermal flux density through the wall and the surface area of the external wall as follows:

$$Q_w = q_w \cdot A_w \tag{1}$$

where Q_w is the heat transfer of the exterior wall, W; A_w is the exterior wall surface area, m^2.

Taking the wall as the research object, the heat balance equation of the vertical greening exterior wall is established as follows:

$$q_w = q_s + q_r + q_c \tag{2}$$

where q_w, q_s, q_r and q_c are, respectively, the heat conduction flow, solar radiation heat flux, long-wave radiation heat flux, and convection heat flux of the exterior wall with VGS, W/m^2.

The heat transfer process of a typical exposed wall has been thoroughly studied, so it is not repeated here. However, when a vertical greening system is applied to the external wall, it will impact the heat transfer. Both the solar radiation heat flux and long-wave radiation heat flux on the outer surface of the wall are affected by the portion of sunlight that passes through the vegetation. The solar radiation heat flux (q_s) can be expressed as follows [13]:

$$q_s = I \cdot \tau_{VGS,t} \cdot \alpha_w \tag{3}$$

where I is total solar radiation intensity, W/m^2; $\tau_{VGS,t}$ is the transmittance for the total solar radiation of the VGS; and α_w is the solar radiation absorbance of the exterior wall surface.

Equation (3) is used to calculate the q_r [13]:

$$q_r = \varepsilon_w \left(I_l \cdot \tau_{VGS,l} + \varepsilon_{VGS} \cdot \sigma \cdot T_{VGS}^4 - \sigma \cdot T_w^4 \right) \tag{4}$$

where ε_w and ε_{VGS} are the emittances of the exterior wall and VGS, respectively; I_l is the incident long-wave radiation, W/m^2; $\tau_{VGS,l}$ is the transmittance for the long-wave radiation of the VGS; σ is the Stephen-Boltzmann constant; and T_{VGS} and T_w are, respectively, the thermodynamic temperature of the VGS and the wall, K.

Equation (5) is used to calculate the q_c:

$$q_c = h_w (t_a - t_w) \tag{5}$$

where h_w is the convective heat transfer coefficient of the exterior wall, W/m^2·K; t_a is the outdoor air temperature, °C; t_w is the exterior wall surface temperature, °C.

Compared to an exposed wall, a wall with a vertical greening system reduces heat transfer into the interior. This reduction in heat helps alleviate the burden on the HVAC system. Vertical greening systems contribute to lowering energy consumption during the building's operational phase and reducing carbon emissions. The energy savings from the vertical greening system can be calculated using the following equation:

$$\Delta Q = Q_{w,e} - Q_{w,VGS} \quad (6)$$

where ΔQ is the energy savings of the exterior wall with VGS, W; $Q_{w,e}$ is the heat transfer of exposed exterior wall, W; and $Q_{w,VGS}$ is the heat transfer of exterior wall with VGS, W.

When the HVAC system uses electricity as the energy drive, the indirect carbon reduction can be calculated by Equation (7):

$$J_{CO_2} = \frac{\sum \Delta Q}{EER} T_{ELE} \quad (7)$$

where J_{CO_2} is the indirect carbon reduction of VGS, kg/a; $\Sigma\Delta Q$ is the total annual energy savings through the vertical greening system, kWh/a; EER is the energy efficiency ratio of the HVAC system; and T_{ELE} is the carbon emission factor of the power system, $kgCO_2/kWh$.

From Equations (3) to (5), it is clear that the vertical greening system affects the heat transfer in all three components mentioned above. Specifically, τ_{VGS}, t, ε_{VGS}, and h_w are closely related to the type of vertical greening, LAI, photosynthesis, and transpiration. Building thermal processes are complex, and their heat balance equations are numerous and difficult to solve. Therefore, directly solving for the impact of a vertical greening system on building energy consumption is nearly impossible. Many studies have explored simplified modeling methods for the thermal performance of vertical greening systems [7,20]. In this study, we draw upon previous research and also employ a simplified thermal performance modeling approach for numerical simulation.

2.2. Calculation of Direct Carbon Sequestration Potential

Plants absorb carbon dioxide and release oxygen through photosynthesis, thereby sequestering carbon. The carbon sequestration process in plants is complex and highly variable, significantly influenced by environmental factors. Quantifying the carbon sequestration capacity of plants through theoretical calculations is challenging.

Current research on quantifying plant carbon sequestration primarily focuses on two methods: measuring carbon sequestration benefits and measuring carbon storage. Both methods typically rely on estimation. One of the most commonly used estimation methods is the photosynthetic rate method. This involves measuring the instantaneous CO_2 concentration and moisture content in and out of the plant leaves using instruments. The plants' carbon sequestration is then calculated by multiplying the leaf area by the net photosynthetic rate per unit time. By measuring the CO_2 concentration and moisture in the leaves, the net assimilation rate per unit leaf area over a certain period is obtained. Using the LAI, the daily CO_2 fixation per unit land area is calculated. Finally, the total CO_2 fixation over a period is determined using the leaf coverage, effective photosynthesis time, and area.

Assuming that the external wall is completely covered by the vertical greening system, excluding the windows, the formula for calculating the annual carbon sequestration of vertical greening plants is as follows:

$$G_{CO_2} = Q_{CO_2} \cdot T \cdot A_w \quad (8)$$

where G_{CO_2} is the annual carbon sequestration of VGS, $kgCO_2/a$; T is the number of days of active photosynthesis in one year, day; A_w is the exterior wall surface area except window,

m^2; and Q_{CO_2} is the daily carbon sequestration of plants per unit area, $kgCO_2/(d \cdot m^2)$, which can be expressed as follows [33]:

$$Q_{CO_2} = W_{CO_2} \cdot LAI \tag{9}$$

where W_{CO_2} is the daily fixed carbon dioxide per unit leaf area, $kgCO_2/(d \cdot m^2)$; and LAI is the effective leaf area index.

The net carbon sequestration of plants should be deducted from the amount of carbon dioxide released by their dark respiration at night, and the consumption of dark respiration of general plants at night is calculated as 20% of the assimilation amount during the day. Therefore, the daily carbon sequestration W_{CO_2} per unit leaf area can be expressed as follows [33]:

$$W_{CO_2} = \mathrm{P}(1 - 0.2) \cdot \frac{44}{1000} \tag{10}$$

where P is the total net assimilative amount of the plant, $mmol/(d \cdot m^2)$; 44 is the molar mass of CO_2; and g/mol; 1000 is the unit conversion.

The LAI of plants can be obtained through direct measurement or by referencing data from relevant literature. The above research method is a simplified estimation. In reality, the carbon sequestration capacity of plants is influenced by many other factors, such as light intensity, temperature, moisture, and nutrient availability, as well as the plant's health and growth stage.

2.3. Comprehensive Carbon Reduction Potential Calculation

By combining the indirect carbon emission reduction and direct carbon sequestration of the vertical greening system, we can evaluate its impact on carbon emissions during the building's operational phase. The total carbon reduction (Z_{CO_2}) of the vertical greening system can be expressed by the following equation:

$$Z_{CO_2} = J_{CO2} + G_{CO2} \tag{11}$$

Through comparison with buildings without a vertical greening system, the carbon reduction rate of vertical greening systems can be better analyzed. Based on the comparison with the carbon emissions of HVAC system energy consumption in the operation stage of buildings without a vertical greening system, the comprehensive carbon reduction rate brought by a vertical greening system is calculated as follows:

$$\theta = \frac{Z_{CO_2}}{\frac{Q}{EER} T_{ELE}} \times 100\% \tag{12}$$

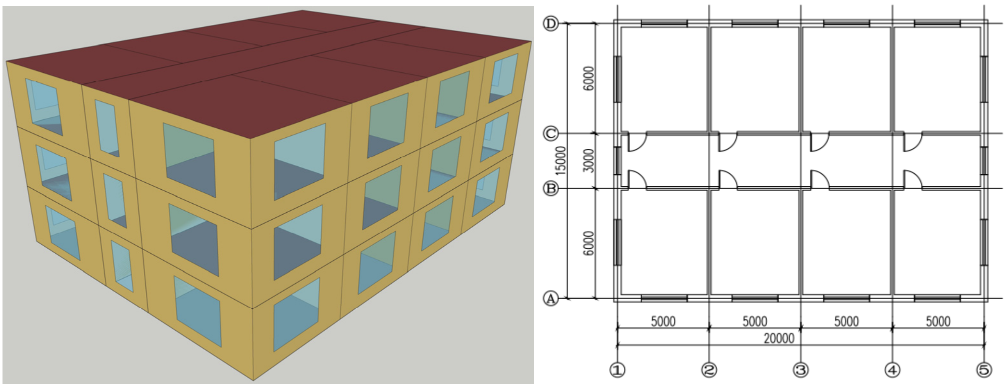
where θ is the carbon reduction rate of the vertical greening system, %; and Q is the total annual energy consumption of HVAC systems during the operating phase of the building, kWh/a.

3. Case Study

There have been many simulation studies on the impact of vertical greening systems on energy consumption, with simulation software such as DesignBuilder, EnergyPlus, and DeST commonly used. Most of these studies assume that vertical greening is an additional building envelope and simulates energy consumption by determining its thermal conductivity. Similarly, in this study, for the sake of simplifying calculations, a typical office building by investigation was selected as the research object, and EnergyPlus 9.2.0 simulation software was used to analyze its energy consumption. To reflect the actual energy-saving effects and comprehensive carbon reduction potential of vertical greening systems, this study examines the impact of vertical greening systems on building energy consumption under different operating conditions. Given that vertical greening systems withered in winter have little effect on building energy consumption and carbon emissions, this study focuses only on the impact of summer green vegetation on building energy consumption and its carbon sequestration potential during the entire green leaf period.

3.1. Building Model and Thermal Performance

The SketchUp model of a typical three-story office building by investigation is shown in Figure 2a, and its floor plan and envelope dimensions are shown in Figure 2b. The floor area of each story is 300 m^2, with a floor height of 3.2 m. The building's form factor is 0.4, and the window-to-wall ratio is 0.3. The thermal parameters of the building envelope used in the simulation are listed in Table 1. It can be seen that the heat transfer coefficient of the building envelope can meet the limit requirements of heat transfer coefficient in energy-saving specifications of different climate zones. The size of the window is set to 2500 × 2400 mm and the solar heat gain coefficient of the window glass is set to 0.35.



(**a**) (**b**)

Figure 2. Model drawings and floor plans of typical office buildings. (**a**) SkepUp model diagram; (**b**) CAD plan of the building.

Table 1. Thermal parameters of typical office building envelopes.

Type of Building Envelop	Composition	Thermal Conductivity W/(m·K)	Thickness m	Overall Heat Transfer Coefficient W/(m^2·K)
Outer wall	Cement mortar	0.93	0.02	0.41
	Rock wool board insulating layer	0.04	0.08	
	Brick wall	0.58	0.12	
	Cement mortar	0.93	0.02	
Roof	Reinforced concrete roof panels	1.74	0.10	0.36
	Mortar screed	0.93	0.02	
	Extruded board insulation layer	0.03	0.08	
	Reinforced concrete protective layer	1.73	0.04	
	Roof tile	0.93	0.03	
Exterior window	Double vacuum glass	/	0.02	3.2

3.2. Vertical Greening System Setup

The type of vertical greening system is an important factor affecting carbon calculations, and the choice of vegetation for vertical greening systems varies across different regions. In this study, the Virginia creeper, commonly used in vertical greening systems, was selected for ease of comparison and analysis. Based on previous studies [34] and considering numerical simulation analysis, three different growth stages of Virginia creeper with LAIs of 3, 2, and 1 were set [29,35]. A scenario with no vertical greening system was also considered for comparison.

To simplify the calculations, it was assumed that the thickness of the Virginia creeper with three different LAIs is 100 mm, and its thermal conductivity values were 0.17, 0.21, and 0.25 W/(m·K) [7], respectively. Due to seasonal temperature variations, the outdoor air temperature differs across regions, resulting in different leafing periods for Virginia creeper throughout the year. During the entire leafing period, the LAI and thermal conductivity are assumed to remain constant. The vertical greening system was applied to the entire building envelope, covering the outer surface of the building, excluding the windows.

3.3. HVAC System Settings

To assess the impact of vertical greening on building operational energy consumption, in addition to providing the building model and envelope parameters, the parameters for the HVAC system must also be specified. Some key parameter settings are shown in Table 2. These parameters are mainly referenced from current Chinese national standards [36], such as the minimum fresh air supply rate for offices, which was set at 30 m^3/(h·person). For ease of comparison, other building parameters, such as occupant density, lighting, and internal heat sources from equipment, remained consistent during the simulation. The work schedule used for the simulation was based on a typical office building's operating hours.

Table 2. Typical office HVAC system design parameter setting table.

Design Parameter Type	Numerical Setting Value
Air condition setting temperature (°C)	26
Air condition relative humidity (%)	50
Heating setting temperature (°C)	20
Heating relative humidity (%)	40
Personnel density (m^2/person)	10
Lighting density (W/m^2)	5
Equipment density (W/m^2)	9
Minimum fresh air volume [m^3/(h·person)]	30

3.4. Simulated Weather Parameter Setting

To understand the impact of vertical greening on carbon emissions during the operational phase of buildings in different climate zones, this simulation selects four representative regions: Xi'an in a cold climate zone, Shanghai in a hot summer and cold winter climate zone, Guangzhou in a hot summer and mild winter climate zone, and Kunming in a temperate climate zone. For better comparison, the thermal performance of envelopes does not change with the different climate zones. These four cities were chosen to represent the characteristics of various climate zones. The changes in outdoor environmental temperature and solar radiation intensity for the typical meteorological year of each region are shown in Figure 3. As can be seen, the outdoor air temperature and solar radiation intensity vary significantly throughout the year in different regions. The maximum values of solar radiation intensity and outdoor air temperature occur in the summer in all regions. The solar radiation intensity in Guangzhou can reach as high as 1318 W/m^2, and the outdoor temperature during summer exceeds 30 °C. All four regions require air conditioning during the summer, and vertical greening will have an impact on the energy consumption in these regions.

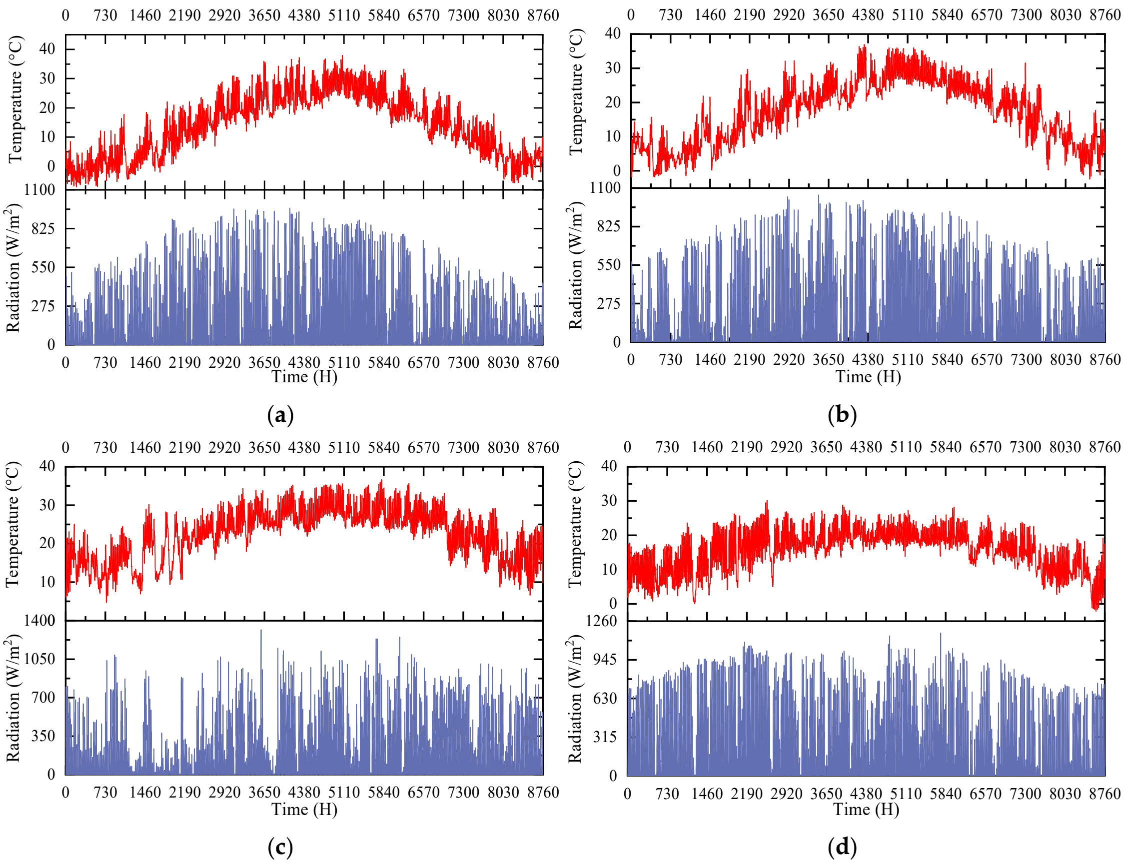


Figure 3. Outdoor meteorological conditions of typical meteorological years in each region. (**a**) Xi'an; (**b**) Shanghai; (**c**) Guangzhou; (**d**) Kunming.

At the same time, considering the operation time of the HVAC system during the energy consumption simulation, the start and end dates of the air conditioning and heating seasons in the four typical regions were surveyed. The results are shown in Table 3. There are differences in the duration of the air conditioning and heating seasons across the regions. Among them, Guangzhou has the longest air conditioning season and no heating season. Kunming has relatively short air conditioning and heating seasons. The operation time of the HVAC system directly impacts the energy consumption and carbon emissions during the building's operational phase.

Table 3. Air conditioning season and heating season time of four typical cities.

Cities	Air Conditioning Season	Heating Season
Xi'an	1 Jun.–30 Sep.	15 Nov.–15 Mar.
Shanghai	1 Jun.–30 Sep.	5 Dec.–7 Mar.
Guangzhou	1 Apr.–31 Oct.	/
Kunming	1 Jun.–31 Aug.	15 Dec.–15 Jan.

4. Results and Discussion

4.1. Analysis of the Energy-Saving Potential of Vertical Greening Systems

The simulation results of the buildings' cooling and heating loads under different vertical greening system conditions are shown in Figure 4. There are significant differences in cooling and heating loads across different regions. In cold regions like Xi'an, the heating load is the highest, while in the hot summer and warm winter region of Guangzhou, the cooling load is the highest, with no heating load. In the moderate climate of Kunming, the heating load is very low. Considering the dormancy of vegetation in winter, the vertical greening system has no effect on the heating load. During the leafing period, the vertical greening system acts as an insulation layer, increasing the thermal resistance of the exterior walls and reducing the building's air conditioning cooling load. Among the regions studied, Guangzhou has the longest air conditioning period, all of which occurs within the leafing period of the vertical greening system. Therefore, the presence of the vertical greening system has the greatest impact on Guangzhou. Additionally, the higher the LAI of the vertical greening system, the greater its effect on the cooling load. Increasing the planting density and LAI of the climbing ivy is beneficial in reducing the air conditioning cooling load.

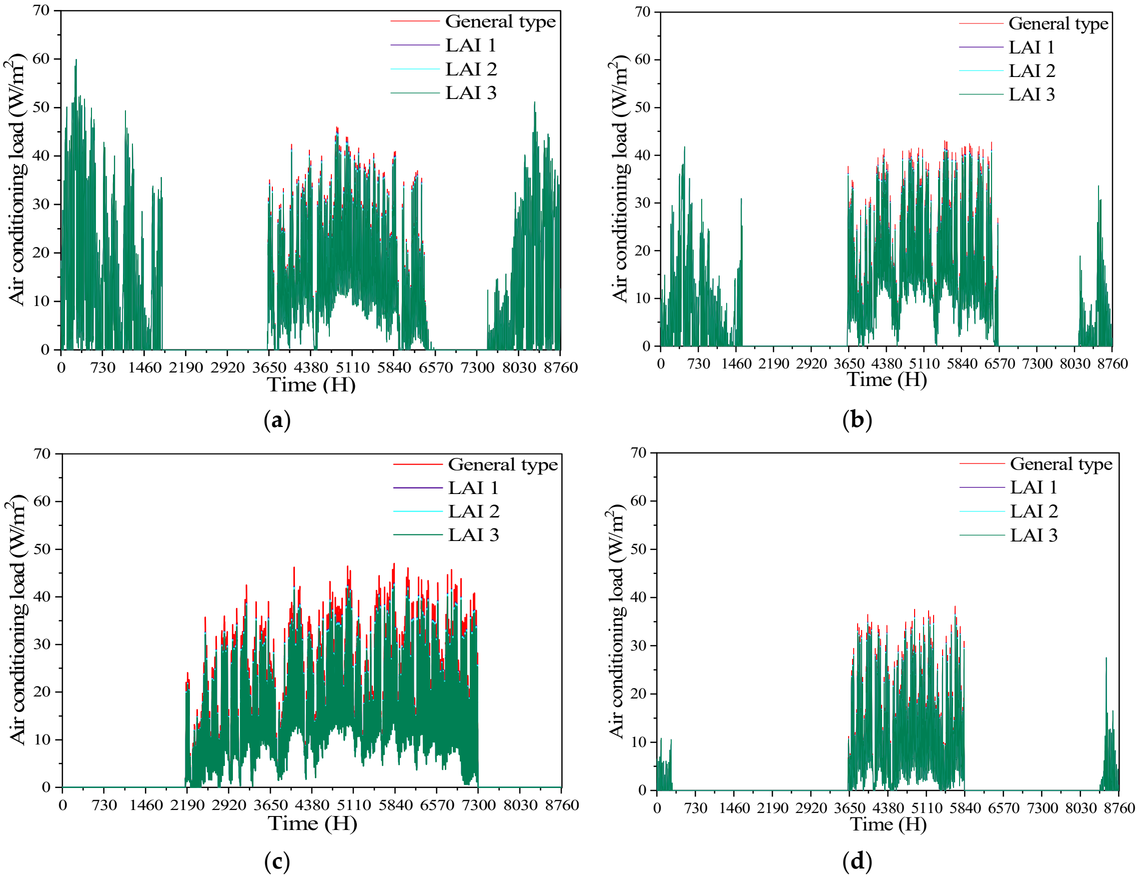


Figure 4. Effects of different degrees of vertical greening on cooling and heat load in different regions. (**a**) Xi'an; (**b**) Shanghai; (**c**) Guangzhou; (**d**) Kunming.

Figure 5 shows the air conditioning and heating energy consumption for four typical regions under different vertical greening system configurations. According to the annual simulation results, due to the influence of outdoor meteorological conditions in each climate zone, the HVAC energy consumption is higher in Xi'an and Guangzhou, and lower in Kunming. Without any vertical greening system, the HVAC energy consumption for the typical buildings in Xi'an, Shanghai, Guangzhou, and Kunming were 81.77, 60.77, 84.83, and 26.09 kWh/m^2, respectively. When a vertical greening system with an LAI of 1 was applied, the HVAC energy consumption in the four regions for the typical building was reduced to 80.82, 58.89, 77.46, and 25.06 kWh/m^2, respectively. The vertical greening system reduces the buildings' annual energy consumption by 1.2%, 3.1%, 8.7%, and 4.0% in the four regions. It is evident that the vertical greening systems have the greatest impact on energy consumption in Guangzhou and the smallest impact in Xi'an. Since the assumption is that the vertical greening system has no effect on heating energy consumption during the winter, a higher annual HVAC energy consumption does not necessarily mean a greater energy-saving potential from the vertical greening system.

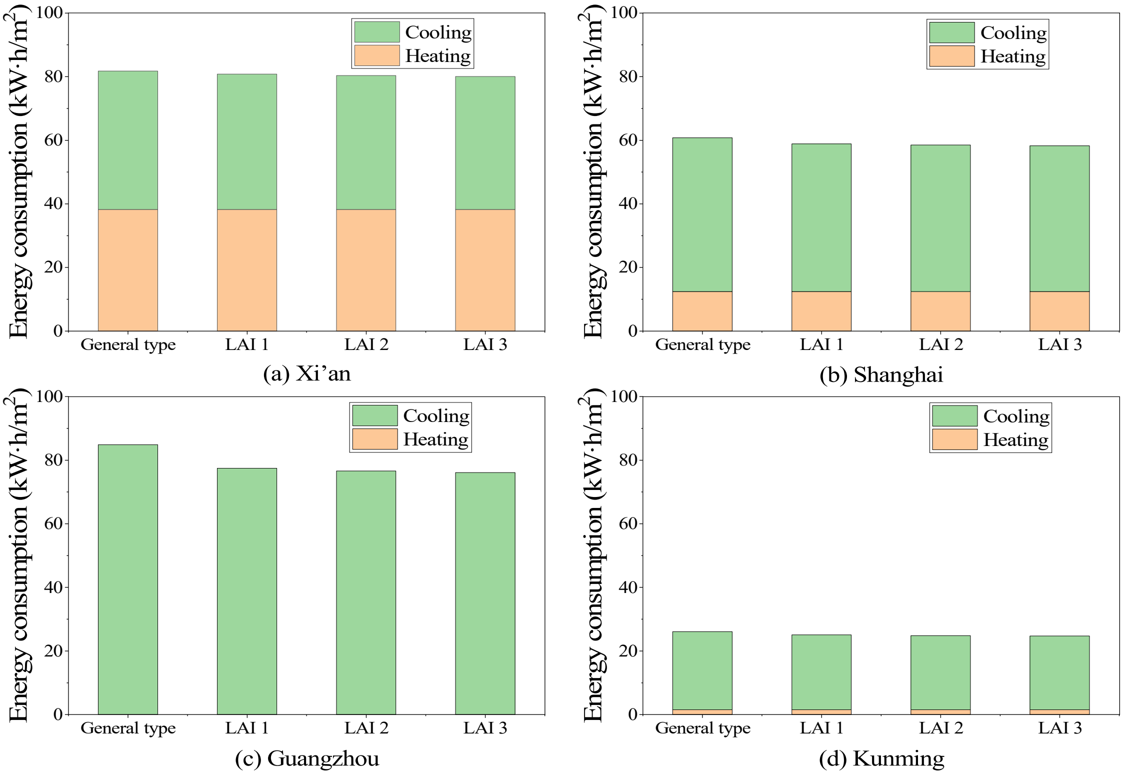


Figure 5. Effects of different degrees of vertical greening on energy consumption in different regions. (**a**) Xi'an; (**b**) Shanghai; (**c**) Guangzhou; (**d**) Kunming.

From the perspective of summer air conditioning energy consumption alone, the higher the LAI of the vertical greening system, the better its energy-saving performance. However, as the LAI increases further, the total energy consumption reduction becomes limited. Taking Guangzhou, the region with the highest energy savings, as an example, the air conditioning energy consumption without any vertical greening system and with leaf area indices of 1, 2, and 3 are 84.84, 77.46, 76.62, and 76.10 kWh/m^2, respectively. It is evident that by progressively increasing the LAI, the energy-saving rates are 8.7%, 9.7%, and 10.3%. Furthermore, from the perspective of the buildings' envelopes, it is found that the better the thermal insulation performance of the building envelope, the smaller the effect of the vertical greening system in reducing energy consumption.

4.2. Analysis of the Energy-Saving and Indirect Carbon Reduction Potential of Vertical Greening Systems

The vertical greening system demonstrated good energy-saving effects in all regions. The energy savings of the HVAC system can be converted into reduced CO_2 emissions based on the system's electricity consumption. The indirect carbon reduction of the vertical greening systems was calculated using Equation (11). The carbon emission factors for the power systems of Xi'an, Shanghai, Guangzhou, and Kunming were set as 0.6671, 0.7035, 0.5271, and 0.5271 $kgCO_2$/kWh, respectively [37]. To simplify the calculation, the system's energy efficiency ratio (EER) was uniformly set to 3.0. The annual indirect carbon reduction for typical office buildings with varying levels of vertical greening in each region is shown in Figure 6. As can be seen from the figure, as the LAI increases, the indirect carbon reduction from energy savings also increases. Guangzhou, with the highest energy savings, also has the largest indirect carbon reduction. When the LAI is 3, the indirect carbon reduction for Guangzhou can reach 1105.45 $kgCO_2/a$. The second highest is Shanghai, with the maximum indirect carbon reduction of 424.56 $kgCO_2/a$. In contrast, the indirect carbon reduction in Xi'an and Kunming is relatively low, mainly due to the smaller energy savings in these regions. This indicates that for regions with high summer air conditioning energy consumption, the vertical greening system has better indirect carbon reduction potential.

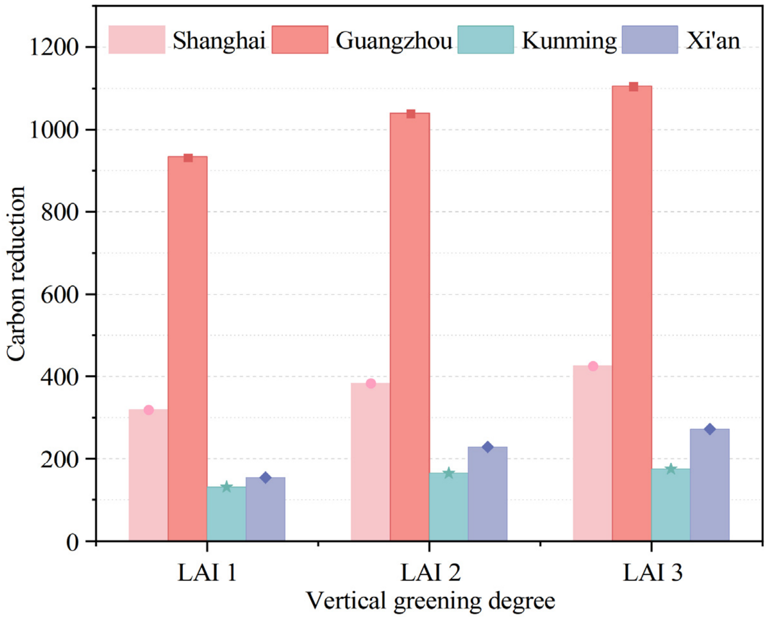


Figure 6. Energy savings and carbon reduction of different degrees of vertical greening in different regions.

4.3. Analysis of Carbon Sequestration Potential of Vertical Greening System

In addition to reducing carbon emissions by lowering HVAC system energy consumption, the vertical greening system also sequesters CO_2 through photosynthesis. According to the theoretical analysis in Section 2.2, the direct carbon sequestration for different levels of vertical greening in typical buildings in various regions was calculated using Formulas (6)–(8). By consulting relevant literature, the length of the green leaf period for Virginia creeper in Xi'an, Shanghai, Guangzhou, and Kunming was set as 200, 210, 300, and 310 days, respectively. To simplify the calculation, the daily carbon sequestration per unit leaf area of Virginia creeper was assumed to be 3.68 $gCO_2/(m^2{\cdot}d)$ for all four regions. Based on these parameter values, the annual carbon sequestration results for typical office buildings with different vertical greening degrees in each region are shown in Figure 7.

Since the daily carbon sequestration per unit leaf area of the Virginia creeper is standardized across the four regions, and the building envelope surface area is also consistent, the total annual carbon sequestration of the vertical greening system is primarily dependent on the length of the plant's green leaf period in each region. In regions with a longer growing season, such as Kunming and Guangzhou, the annual carbon sequestration is higher. In Kunming, when the LAI is 3, the annual carbon sequestration can reach 1609.90 $kgCO_2/a$. Even in Xi'an, with an LAI of 1, it can still reach 346.21 $kgCO_2/a$. This demonstrates that vertical greening can result in a substantial amount of carbon sequestration. Even without considering the indirect carbon reduction brought about by energy savings, it still holds great potential for application.

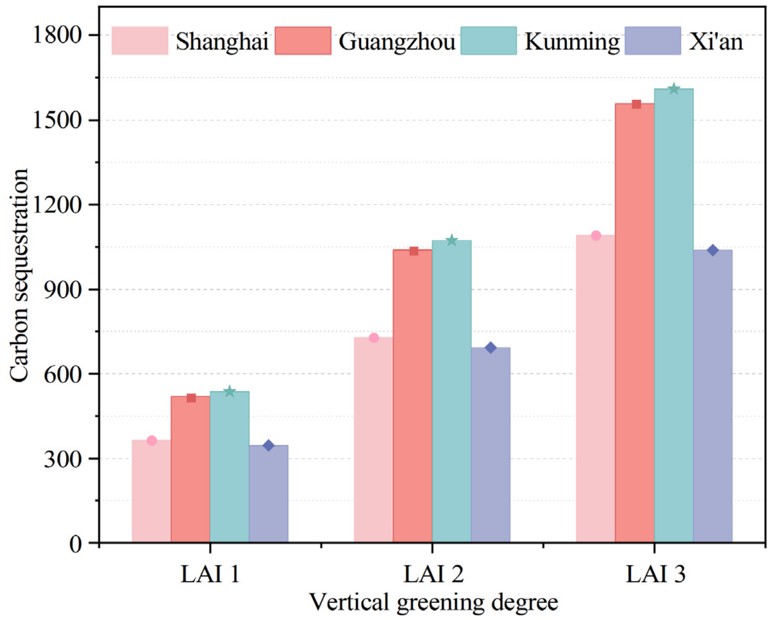


Figure 7. Carbon sequestration potential of different degrees of vertical greening in different regions.

4.4. Comprehensive Carbon Reduction Potential Analysis of Vertical Greening System

By adding the indirect carbon reduction and direct carbon sequestration amounts, the comprehensive carbon reduction potential of the vertical greening system is shown in Figure 8. The comprehensive carbon reduction potential is greatest in Guangzhou, reaching 2663.42 $kgCO_2/a$, while the lowest is in Xi'an, at only 499.60 $kgCO_2/a$. The proportion of indirect carbon reduction and direct carbon sequestration varies across different regions. Overall, the direct carbon sequestration amount is higher than the indirect carbon reduction amount. Among the regions, Kunming has the highest proportion of direct carbon sequestration in the overall carbon reduction, with a share of over 90% when the LAI is 3. In contrast, Guangzhou has the lowest proportion of direct carbon sequestration in the overall carbon reduction, with only 35.74% when the LAI is 1. This is because Guangzhou experiences the highest air conditioning energy consumption in summer, and vertical greening can provide a relatively significant energy-saving effect. In conclusion, regardless of the climate zone, the vertical greening system can contribute significantly to carbon reduction and provide strong support for the building industry in achieving carbon neutrality goals. For hot summer climates and regions with long green leaf periods, such as Guangzhou, the vertical greening system offers even greater comprehensive carbon reduction potential.

4.5. Limitations and Prospects

This study quantifies the positive impact of vertical greening on carbon emissions during the building operation phase through a simplified calculation method, analyzing its comprehensive carbon reduction potential from both energy-saving and photosynthetic carbon sequestration perspectives. The research findings can promote the application of vertical greening in buildings and guide the selection of vertical greening systems for carbon emission reduction in different climate zones. However, as this study is based on simulations and calculations, there are some limitations that warrant further detailed research in the future.

Firstly, although the evaluation method of this study is simple, it is conducive to engineering application and calculation analysis. Due to the lack of experimental conditions, future studies will include experimental studies to improve the confidence of the findings. Secondly, this study assumes that vertical greening covers the entire exterior wall, which is simplified into the additional heating resistance of the envelope. The effects of plant photosynthesis and transpiration on comprehensive carbon emission potential under different solar radiation conditions were not considered. Future studies can be conducted to investigate the dynamic changes of carbon sequestration during the growth of vertical greening plants. Lastly, when applying vertical greening systems to buildings, the growth conditions over their lifecycle should also be considered, such as the impact of the sprouting and leaf-shedding periods on building energy consumption. Future studies could involve a comprehensive carbon reduction potential analysis throughout the full growth cycle, including evaluations of carbon sequestration under varying solar radiation intensities and different growth stages.

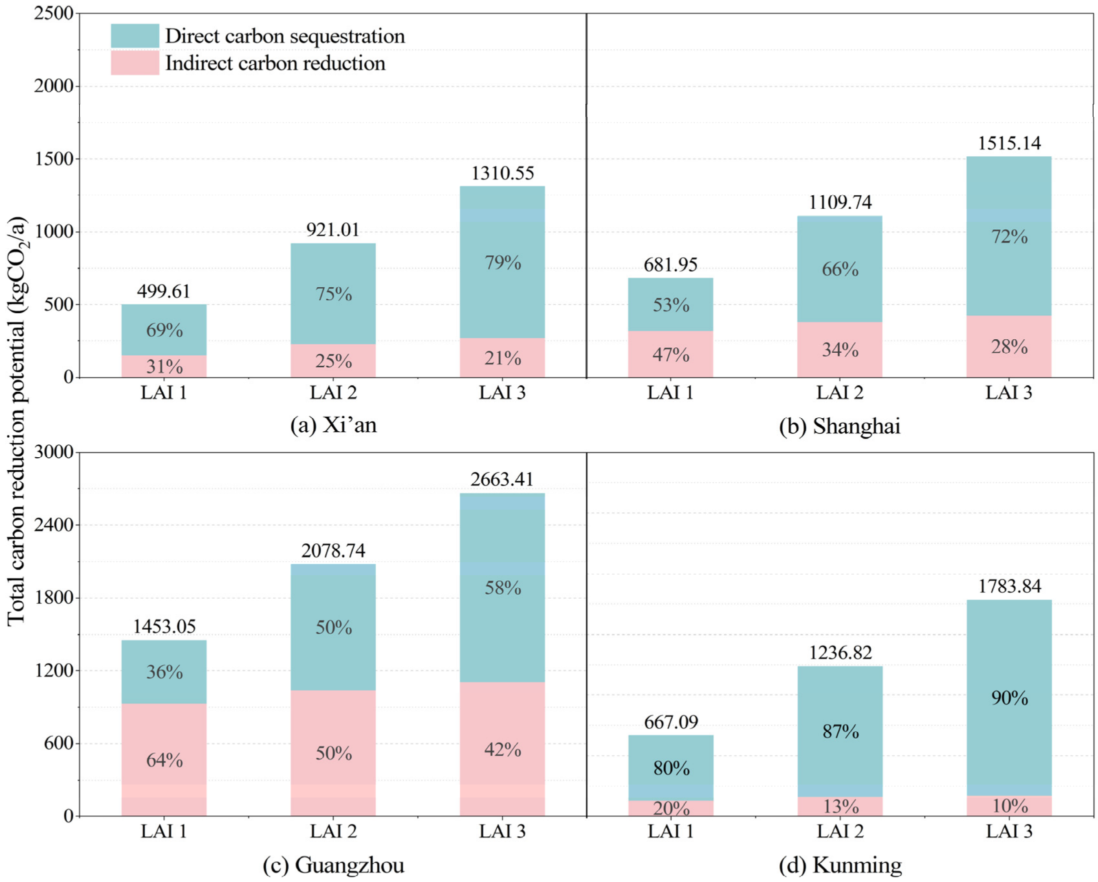


Figure 8. Comprehensive carbon reduction potential of different vertical greening degrees in different regions. (**a**) Xi'an; (**b**) Shanghai; (**c**) Guangzhou; (**d**) Kunming.

5. Conclusions

This study proposes a simplified calculation method for the comprehensive carbon reduction potential of vertical greening systems. Indirect carbon reduction is determined through energy consumption simulations of the vertical greening system, and this is added to the direct carbon sequestration achieved through photosynthesis. Using a typical office building as an example, a comprehensive carbon reduction potential analysis is conducted for four cities: Xi'an, Shanghai, Guangzhou, and Kunming. The following key conclusions were drawn:

(1) The vertical greening systems reduced the buildings' annual energy consumption. In Xi'an, Shanghai, Guangzhou, and Kunming, energy consumption was reduced by 1.2%, 3.1%, 8.7%, and 4.0%, respectively. The system had the greatest impact on

energy consumption in Guangzhou, where the air conditioning period is the longest. Increasing the planting density of the vertical greening system and enhancing the leaf area index of ivy helps reduce cooling loads.

(2) Guangzhou, which achieved the highest energy savings, also has the greatest indirect carbon reduction. When the LAI is 3, the indirect carbon reduction in Guangzhou can reach 1105.45 kgCO_2/a. Vertical greening systems have better indirect carbon reduction potential in regions with high air conditioning energy consumption during the summer.

(3) The total annual carbon sequestration of the vertical greening system is mainly influenced by the duration of the green leaf period in the region. Vertical greening systems in Kunming and Guangzhou, where the growing season is longer, have a higher total annual carbon sequestration. In Kunming, when the LAI is 3, the annual carbon sequestration can reach 1609.90 kgCO2/a. Even without considering the indirect carbon reduction from energy savings, vertical greening can still provide significant carbon sequestration.

(4) Guangzhou shows the highest comprehensive carbon reduction potential, while Xi'an shows the lowest. The proportion of indirect carbon reduction and direct carbon sequestration varies between regions, with direct carbon sequestration generally being slightly higher than indirect reduction. In regions with hot summers and long green leaf periods, such as Guangzhou, vertical greening systems offer greater comprehensive carbon reduction potential. Regardless of the climate zone, vertical greening systems can effectively contribute to carbon reduction and provide strong support for achieving the dual carbon goals in the building sector.

Author Contributions: Conceptualization, T.L.; Methodology, T.L.; Software, T.W.; Formal analysis, H.M.; Investigation, S.W.; Data curation, T.W.; Writing—original draft, H.M. and T.L.; Project administration, S.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: Authors Hongtu Mi and Shidong Wang were employed by the company Gansu Institute of Architectural Design and Research Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Nomenclature

A	Surface area, m^2
A_w	Exterior wall surface area except window, m^2
EER	Energy efficiency ratio of HVAC system
G_{CO_2}	Annual carbon sequestration of VGS, $kgCO^2/a$
h	Convective heat transfer coefficient, $W/m^2 \cdot K$
I	Total solar radiation intensity, W/m^2
J_{CO_2}	Indirect carbon reduction of VGS, kg/a
LAI	Effective leaf area index
P	Total net assimilative amount of the plant, mmol/(d·m^2)
Q	Heat transfer, W/Total annual energy consumption of HVAC systems during the operating phase of the building, kWh/a
ΔQ	Energy savings of exterior wall with VGS, W
$\Sigma\Delta Q$	Total annual energy savings through the vertical greening system, kWh/a

Q_{CO_2}	Daily carbon sequestration of plants per unit area, $kgCO_2/(d \cdot m^2)$
q_w	Heat conduction flow of the exterior wall with VGS, W/m^2
q_s	Solar radiation heat flux of the exterior wall with VGS, W/m^2
q_r	Long wave radiation heat flux of the exterior wall with VGS, W/m^2
q_c	Convection heat flux of the exterior wall with VGS, W/m^2
T	Thermodynamic temperature, °C/Number of days of active photosynthesis in one year
$TELE$	Carbon emission factor of the power system, $kgCO^2/kWh$
t_a	Outdoor air temperature, °C
t_w	Exterior wall surface temperature, °C
W_{CO_2}	Daily fixed carbon dioxide per unit leaf area, $kgCO_2/(d \cdot m^2)$
σ	Stephen–Boltzmann constant
τ	Transmittance for the total solar radiation
α	Solar radiation absorbance
ε	Emittances
θ	Carbon reduction rate of the vertical greening system, %
VGS	Vertical greening system
w/e	Exterior wall
l	Long-wave radiation

References

1. Chen, H.; Cao, R.; Yuan, T.; Huo, T.; Cai, W. Are the Later-Urbanized Regions More Energy-Efficient in the Building Sector? Evidence from the Difference-in-Differences Model. *J. Clean. Prod.* **2023**, *384*, 135644. [CrossRef]
2. Ma, M.; Ma, X.; Cai, W.; Cai, W. Low Carbon Roadmap of Residential Building Sector in China: Historical Mitigation and Prospective Peak. *Appl. Energy* **2020**, *273*, 115247. [CrossRef]
3. Balali, A.; Yunusa-Kaltungo, A.; Edwards, R. A Systematic Review of Passive Energy Consumption Optimisation Strategy Selection for Buildings through Multiple Criteria Decision-Making Techniques. *Renew. Sustain. Energy Rev.* **2023**, *171*, 113013. [CrossRef]
4. Li, T.; Liu, X.; Li, G.; Wang, X.; Ma, J.; Xu, C.; Mao, Q. A Systematic Review and Comprehensive Analysis of Building Occupancy Prediction. *Renew. Sustain. Energy Rev.* **2024**, *193*, 114284. [CrossRef]
5. Pérez, G.; Coma, J.; Martorell, I.; Cabeza, L.F. Vertical Greenery Systems (VGS) for Energy Saving in Buildings: A Review. *Renew. Sustain. Energy Rev.* **2014**, *39*, 139–165. [CrossRef]
6. Zuo, J.; Zhao, Z.-Y. Green Building Research–Current Status and Future Agenda: A Review. *Renew. Sustain. Energy Rev.* **2014**, *30*, 271–281. [CrossRef]
7. Guo, X.; Chen, X.; Yu, Y.; Wei, S.; Chen, W. A Simplified Modeling Method for Studying the Thermal Performance of Buildings with Vertical Greening Systems. *J. Clean. Prod.* **2024**, *467*, 142940. [CrossRef]
8. Vox, G.; Blanco, I.; Schettini, E. Green Façades to Control Wall Surface Temperature in Buildings. *Build. Environ.* **2018**, *129*, 154–166. [CrossRef]
9. Bao, S.; Zou, S.; Li, B.; Chen, Q.; Zhao, M. Experiments on the Cooling Effect of Modular Vertical Greening on Double-Glazed Façade in Summer. *Build. Environ.* **2022**, *226*, 109771. [CrossRef]
10. Turhan, C.; Özbey, M.F.; Çeter, A.E.; Akkurt, G.G. A Novel Data-Driven Model for the Effect of Mood State on Thermal Sensation. *Buildings* **2023**, *13*, 1662. [CrossRef]
11. Özbey, M.F.; Çeter, A.E.; Örfioglu, S.; Alkan, N.; Turhan, C. Sensitivity analysis of the effect of current mood states on the thermal sensation in educational buildings. *Indoor Air* **2022**, *32*, 13073. [CrossRef]
12. Wahba, S.; Kamel, B.; Nassar, K.; Abdelsalam, A. Effectiveness of Green Roofs and Green Walls on Energy Consumption and Indoor Comfort in Arid Climates. *Civ. Eng. J.* **2018**, *4*, 2284. [CrossRef]
13. Nesci, V.; Ballarini, I.; Rando Mazzarino, P.; Corrado, V. Living Walls and Green Façades: An Implementation Code for Energy Simulation. *Buildings* **2024**, *14*, 2040. [CrossRef]
14. Susorova, I.; Azimi, P.; Stephens, B. The Effects of Climbing Vegetation on the Local Microclimate, Thermal Performance, and Air Infiltration of Four Building Facade Orientations. *Build. Environ.* **2014**, *76*, 113–124. [CrossRef]
15. Liu, Y.; Chen, Y.; Wang, D.; Li, T. Research of Vertical Green Impact on the Indoor Thermal Environment. *J. Xi'an Univ. Arch. Technol. (Nat. Sci. Ed.)* **2015**, *47*, 423–426. (In Chinese)
16. Morakinyo, T.E.; Lai, A.; Lau, K.K.-L.; Ng, E. Thermal Benefits of Vertical Greening in a High-Density City: Case Study of Hong Kong. *Urban For. Urban Green.* **2019**, *37*, 42–55. [CrossRef]

17. Zhu, S.; Causone, F.; Gao, N.; Ye, Y.; Jin, X.; Zhou, X.; Shi, X. Numerical Simulation to Assess the Impact of Urban Green Infrastructure on Building Energy Use: A Review. *Build. Environ.* **2023**, *228*, 109832. [CrossRef]
18. Coma, J.; Pérez, G.; de Gracia, A.; Burés, S.; Urrestarazu, M.; Cabeza, L.F. Vertical Greenery Systems for Energy Savings in Buildings: A Comparative Study between Green Walls and Green Facades. *Build. Environ.* **2017**, *111*, 228–237. [CrossRef]
19. Li, Z.; Chow, D.H.C.; Yao, J.; Zheng, X.; Zhao, W. The Effectiveness of Adding Horizontal Greening and Vertical Greening to Courtyard Areas of Existing Buildings in the Hot Summer Cold Winter Region of China: A Case Study for Ningbo. *Energy Build.* **2019**, *196*, 227–239. [CrossRef]
20. Zhang, Y.; Zhang, L.; Meng, Q. Dynamic Heat Transfer Model of Vertical Green Façades and Its Co-Simulation with a Building Energy Modelling Program in Hot-Summer/Warm-Winter Zones. *J. Build. Eng.* **2022**, *58*, 105008. [CrossRef]
21. Karimi, K.; Farrokhzad, M.; Roshan, G.; Aghdasi, M. Evaluation of Effects of a Green Wall as a Sustainable Approach on Reducing Energy Use in Temperate and Humid Areas. *Energy Build.* **2022**, *262*, 112014. [CrossRef]
22. Haggag, M.; Hassan, A.; Elmasry, S. Experimental Study on Reduced Heat Gain through Green Façades in a High Heat Load Climate. *Energy Build.* **2014**, *82*, 668–674. [CrossRef]
23. Perini, K.; Ottelé, M.; Giulini, S.; Magliocco, A.; Roccotiello, E. Quantification of Fine Dust Deposition on Different Plant Species in a Vertical Greening System. *Ecol. Eng.* **2017**, *100*, 268–276. [CrossRef]
24. Yang, Y.; Hu, K.; Liu, Y.; Wang, Z.; Dong, K.; Lv, P.; Shi, X. Optimisation of Building Green Performances Using Vertical Greening Systems: A Case Study in Changzhou, China. *Sustainability* **2023**, *15*, 4494. [CrossRef]
25. Pan, L. *Carbon Sequestration and Thermal Performance of Vertical Greening*; The Chinese University of Hong Kong: Hong Kong, China, 2016.
26. Marchi, M.; Pulselli, R.M.; Marchettini, N.; Pulselli, F.M.; Bastianoni, S. Carbon Dioxide Sequestration Model of a Vertical Greenery System. *Ecol. Model.* **2015**, *306*, 46–56. [CrossRef]
27. Zaid, S.M.; Perisamy, E.; Hussein, H.; Myeda, N.E.; Zainon, N. Vertical Greenery System in Urban Tropical Climate and Its Carbon Sequestration Potential: A Review. *Ecol. Indic.* **2018**, *91*, 57–70. [CrossRef]
28. Li, X.; Ramos Aguila, L.C.; Wu, D.; Lie, Z.; Xu, W.; Tang, X.; Liu, J. Carbon Sequestration and Storage Capacity of Chinese Fir at Different Stand Ages. *Sci. Total Environ.* **2023**, *904*, 166962. [CrossRef] [PubMed]
29. De Bock, A.; Belmans, B.; Vanlanduit, S.; Blom, J.; Alvarado-Alvarado, A.A.; Audenaert, A. A Review on the Leaf Area Index (LAI) in Vertical Greening Systems. *Build. Environ.* **2023**, *229*, 109926. [CrossRef]
30. Charoenkit, S.; Yiemwattana, S. Role of Specific Plant Characteristics on Thermal and Carbon Sequestration Properties of Living Walls in Tropical Climate. *Build. Environ.* **2017**, *115*, 67–79. [CrossRef]
31. Gratani, L.; Varone, L.; Bonito, A. Carbon Sequestration of Four Urban Parks in Rome. *Urban For. Urban Green.* **2016**, *19*, 184–193. [CrossRef]
32. Yang, S.; Kong, F.; Yin, H.; Zhang, N.; Tan, T.; Middel, A.; Liu, H. Carbon Dioxide Reduction from an Intensive Green Roof through Carbon Flux Observations and Energy Consumption Simulations. *Sustain. Cities Soc.* **2023**, *99*, 104913. [CrossRef]
33. Zhou, Y.; Chen, R. A Study on the Benefits of Carbon Fixation and Oxygen Release of Spring Spontaneous Plants for Roof Greening in Chengdu. *J. Green Sci. Technol.* **2023**, *25*, 40–46. (In Chinese)
34. Wong, N.H.; Tan, A.; Puay Yok, T.; Wong, N. Energy Simulation of Vertical Greenery Systems. *Energy Build.* **2009**, *41*, 1401–1408. [CrossRef]
35. Ning, B.; Yu, H.; He, Y.; Zhao, M. Influence of Vertical Greening on Energy Simulation of Office Building in Southern Region. *Build. Energy Environ.* **2016**, *12*, 33–36. (In Chinese)
36. *GB 50736-2012*; Design Code for Heating Ventilation and Air Conditioning of Civil Buildings. Ministry of Housing and Urban-Rural Development (MHURD): Beijing, China, 2012. (In Chinese)
37. *GB/T51366-2019*; National Standard for Building Carbon Emission Calculation. Ministry of Housing and Urban-Rural Development (MHURD): Beijing, China, 2019. (In Chinese)