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Selection of suitable plant species for energy efficient Vertical Greenery Systems (VGS)

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Abstract

Vertical Greenery Systems (VGS) are getting popular in congested urban cities throughout the world. The selection of suitable plant species heavily influences the success of VGS. Plant selection principles of VGS are barely discussed in existing literature. Therefore, this paper intends to explore factors influencing selection of plants in detail. The paper discusses the plant characteristics and plant selection principles. Furthermore, EnergyPlus simulations have been performed based on a case study in Hong Kong to demonstrate the effect of different plant characteristics on energy saving. The results show that leaf area index is the most influential plant parameter in thermal performance of VGS. The study highlights the importance of selecting suitable plant species in enhancing the energy benefits of VGS.

Peer-review under responsibility of the scientific committee of the 9th International Conference on Applied Energy.

Keywords: Vertical greenery systems; plant species; plant characteriscs; energy saving

1. Introduction

Vertical greening is gaining popular as a viable option of enhancing the passive thermal performance of buildings while integrating greenery into urban inhabitants [1]. Many decades ago building facades were decorated with self-climbing plants and vines [2]. In present, traditional architectural features along with advanced materials and technology are used to enhance the design flexibility of VGS. Green facades and the living walls are the most

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extensively used classification for VGS. Green facades use climbing plants which are rooted on the ground. Whereas in living walls plants are rooted on a growing medium attached upright to a vertical facade [1]. Proper selection of plant species is a major success factor of VGS. Physiological/morphological traits of plants greatly influence the energy benefit of VGS [3]. Selection of plant species depends on number of factors including preferred visual effect, availability of plant species, requirement of water and nutrient, environmental conditions and system configuration [2]. Therefore, this paper explores plant characteristics and plant selection principles in detail. Furthermore, EnergyPlus simulations are performed to show the effect of plant characteristics on energy saving. The finding of the paper provides guidance to select most appropriate species among the wide range of limitless plants.

2. Plant characteristics

Different plants have different characteristics including structural parameters (height and leaf area index (LAI)), radiative properties (albedo and emissivity), plant traits (leaf hairiness, colour, thickness), and processes (stomatal conductance/leaf water loss) [4,3]. Among these LAI is considered as the most critical parameter in defining the thermal effect from plants. LAI is used to characterize leaf mass of set of plants, which is defined as the one sided leaf area per unit wall surface area (LAI = leaf area/ground area, m^2/m^2) which is a dimensionless quantity [5,6]. Height of plant is another structural parameter which affect the wind speed in the foliage. Short plants tend to have many stems and dead matter with a large vegetation cover. Leaf emissivity is the thermal radiation emitted from leaf surface, which plays an important role in obtaining net radiation via outgoing long-wave radiation [7]. Leaf reflectivity (albedo) is the fraction of incident solar radiation reflected by the leaf [8]. These radiative properties depend on the type, season, leaf color, texture and plant age. Lighter leaf color and longer hair length species like *Heuchera* and *Salvia* have lower leaf temperatures [3], whereas dark color leaves absorbed more energy [4]. Leaves with lesser leaf thickness helps to maintain leaf temperature at lower values allowing higher heat dissipation. Stomatal resistance represents the rate of water vaporization on leaf surface. This tends to change with environment conditions to conserve moisture in plants.

3. Plant selection principles

The selection of suitable plant species also effects on the type of VGS, design goals, fire protection and maintenance requirements and environment conditions. The type of VGS is the first factor should be considered while choosing plants since supporting structure and soil depth differ. Green facades require climbing plants such as *Hedera helix, Parthenocissus quinquefolia* and *Ficus pumila.* An increased species diversity is observed in green facades with vertical support. Living wall systems allow a wider variety of plant species including shrubs, grasses and perennials [9]. The main design goals of VGS are considered as visual effects, energy benefits and air quality improvement. Visual criteria mainly include four aspect: winter or dormant-season interest, flowering, variety of form and foliage [10]. A mix of succulents, herbaceous perennials and annuals may be combined to achieve better visual interest in the whole year [11]. Vegetation perform well in trapping dust and pollutants. The effectiveness and LAI have positive correlation with trapping dust [10]. An increased plant coverage can reduce solar radiation absorbed by soil surface as well as the increase near surface moisture content [12].

All greenery requires some degree of maintenance as they are living systems, Proper maintenance of irrigation system is critically important for long-term survivability. Fire spreading is a potential hazard of VGS. Inadequate irrigation may dry out the plants, creating a favourable condition for fire. However, vegetation hardly be ignited if it is kept green and alive [13]. Environment condition is one of the dominated factors influencing plant survival. Salt spray or salt in mists in coastal areas and acid rain from industrial areas can affects plant selection [11]. In addition, heat accumulation will be harmful for most plants in hotter climates [11]. Since growing medium is thin, plants should be drought tolerance and able to survive in harsh weather conditions [10].

4. Methodology

To explore the effect of different plant species on building cooling load, EnergyPlus simulations have been performed. EnergyPlus is a widely accepted open-source energy simulation package developed by the U.S. Department of Energy based on the fundamental heat balance principle. It is freely available on https://energyplus.net/.

It can simulate indoor thermal environments together with mechanical and electrical systems incorporating building descriptions [8]. However, at the current scope of EnergyPlus, the thermal effect of vegetation could not be simulated. Therefore, in order to simulate thermal effect of VGS, a module has been developed and validated in our previous study [14]. The developed module is based on the heat balance principle of soil and plant layer as shown in Figure 1 (a). It has been integrated into EnergyPlus to calculate the impact of VGS on building energy. This module accounts for long-wave and short-wave radiation exchange within the plant canopy, convective heat transfer effect of the plant canopy, evapotranspiration and heat conduction in the soil layer.

To demonstrate the effect of different plant parameters on building energy consumption, a hypothetical high-rise office building based on Hong Kong is modeled in EnergyPlus. Figure 1 (b) shows the schematic diagram of the building model. Hong Kong has a hot-humid climate, located at latitude 22° 19' N and longitude 114° 10' E. The simulation uses EnergyPlus weather files with typical meteorological year data. The details of the scenario is provided in Table 1. The LAI and height of plants are considered as the key structural parameters for simulation. The VGS is integrated to the west facade of the building, since previous studies showed that west orientation provide higher thermal benefits. Ten (10) scenarios have been simulated by varying LAI and plant height. Annual cooling load is obtained for each scenario and compared with a reference case without greenery.

Table 1. Simulation details.

Building Details - Office		**Details of VGS** [12]	
Dimensions (L×W×H)	50 m × 50 m × 100 m, 3 m floor height	Height of plants (m)	0.05, 0.1, 0.2, 0.3, 0.4
Window-wall ratio	50 %	Leaf area index	1,2,3,4,5
HVAC systems details	Variable Air Volume (VAV) Ideal load system, Cooling set point – 24°C	Leaf emissivity	0.9
		Minimum stomatal resistance	100 s/m
Internal heat gains	People – 18.6 m^2 per person/ person	Leaf reflectivity	0.2
	Lights – 10.8 W/m^2	Soil thickness	0.1 m
	Electrical Equipment – 10.8 W/m^2	Conductivity of dry soil	0.4 W/m.k

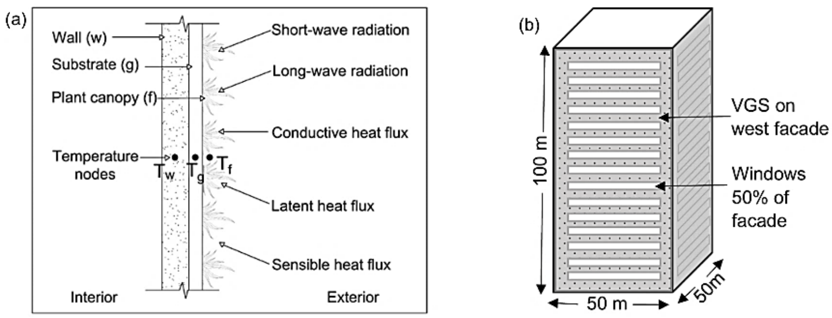

Fig. 1. (a) Heat fluxes account in the VGS model (b) Schematic diagram of EnergyPlus building model

5. Results and analysis

5.1. Influence of LAI on building energy consumption

The surface temperatures and heat flux of VGS under different LAI values will provide clear understanding of its thermal influence. The maximum thermal impact of VGS can obtain on the hottest summer day. Therefore, surface temperature, sensible heat flux and latent heat flux transfer through VGS is obtained on the hottest summer day which is 1st of July per the typical weather data with maximum dry bulb temperature of 32.8 °C. The different LAI values simulated include 1,2,3,4 and 5 while plant height remained 0.3 m. As shown in Figure 2 (a), the increase of LAI from 1 to 5, significantly reduced the exterior surface temperature of VGS from 52 °C to 40 °C. Similar results were presented by Susorova [15] on a hot summer day in Phonex, USA, where exterior surface temperature of VGS was decreased by 12.3 ºC with increase of LAI from 1 to 4. Also Fernández-Bregón et al. [16] showed that exterior surface temperature of a wall can be significantly reduced with a vegetation cover, where this study achieved 5 ºC temperature decrease with VGS in Chile on a winter day. As shown in Figure 2 (b) and Figure 2 (c) sensible and latent heat transfer through VGS reduces with increase of LAI. The peak value of the sensible heat transfer reduced from 60 W/m^2 to 12 W/m^2, and latent heat transfer reduced from 66 W/m^2 to 26 W/m^2 when LAI increased from 1 to 5. These results show that plants with higher LAI increase the shading effect and effectively control the heat transfer into the building.

Building cooling load reduction with respect to different LAI is presented in Figure 3. The results show that cooling load reduction is higher during summer months (June – August) than in winter months (December – February), with maximum reduction in July. It should be noted that in Hong Kong, even during winter period the outdoor air temperature reaches higher values, demanding cooling. For all LAI values, the monthly cooling load reduction shows a similar trend with higher saving when LAI increases. In the month of July, the cooling load saving was 3.8 kWh/m^2 with LAI = 1, which is increased up to 10 kWh/m^2 when LAI = 5. In January, which is the coldest winter month only 0.6 kWh/m^2, cooling load reduction is achieved with LAI = 5 and a negative value with LAI =1. The negative values in cooling load reduction mean that cooling load is increased. This is due to the insulating effect of VGS. It shows that during winter period VGS with lower plant coverage create an insulting effect instead of a cooling effect. Figure 3 (b) illustrate the annual cooling load reduction as a percentage value. There is a positive nonlinear relationship among LAI and the cooling load reduction. The annual cooling load reduction increased from 0.4 % to 1.8% when LAI increases from 1 to 5. These results emphasize the importance of using plant species with higher LAI for enhancing the energy benefits. This is consistent with the experimental study by Coma et al [17], which showed that when solar radiation is higher, VGS can provide higher energy saving where this study resulted 34% cooling energy saving during summer period with LAI of 3.5 – 4 under Mediterranean climate. It should be noted that the amount of energy saving heavily depends many external factors such as climate, scale of building and internal heat gains. A study by Cameron et al. [18] also showed that thicker canopies in VGS provide higher cooling potential.

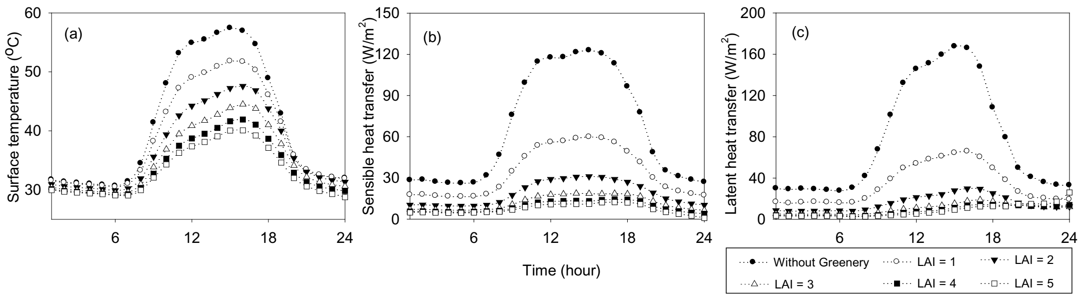

Fig. 2. Thermal performance of VGS on hottest summer day (a) Surface temperature; (b) Sensible heat flux; (c) Latent heat flux

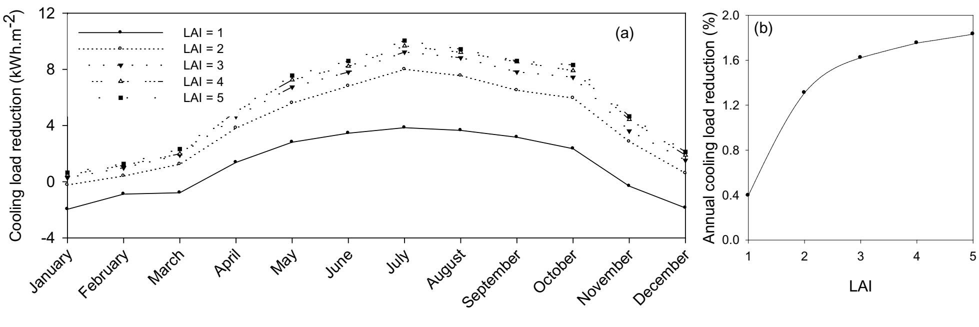

Fig. 3. Cooling load reduction with different LAI (a) Monthly (kWh.m^{-2}); (b) Annually (%).

5.2. Influence of plant height on building energy consumption

Figure 4 (a) represents the variation of monthly cooling load reduction with change of plant height. The simulated plant height varied from 0.05 m to 0.4 m, while LAI =1. As expected higher benefits are shown during the summer period (June – August) compared to the winter months (December – February). However, the effect of plant height on cooling load demand is not significant. Especially, during the winter months the effect of plant height is negligible. During April to October, the benefits are slightly higher with the plants with lesser height. The peak cooling load reduction is recorded in month of July with 4.4 kWh/m^2 with the plant height of 0.05 m. When the plant height increases to 0.4 m, the peak cooling load reduction is decreased from 0.6 kWh/m^2, resulting 3.8 kWh/m^2 saving. These results are compatible with the experiment findings such as by Monteiro et al. [4] which showed that plants height is not a significant factor influencing cooling load. In January, which is the coldest winter month cooling load reduction shows negative values meaning that insulation effect of VGS increases the building cooling demand. The effect on annual cooling load reduction is represented in Figure 4 (b) which shows a negative nonlinear relationship. The increase of height from 0.05 m to 0.4 m cause reduction of cooling load benefits from 0.09 %. These results show that it is better to use shorter plants in VGS to enhance the energy benefits.

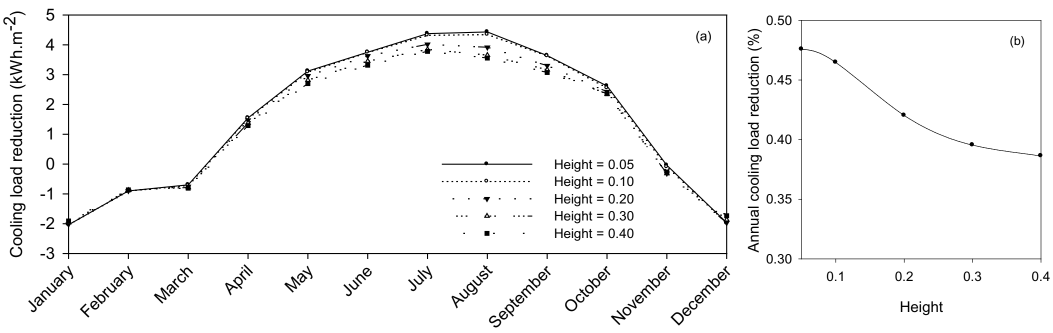

Fig. 4. Cooling load reduction with different height of plants (a) Monthly (kWh.m^{-2}); (b) Annually (%).

5.3. Selection process of suitable plant species

The selection of plant species heavily impact on the performance of VGS. Plant characteristics can be categorised under four groups as structural parameters, radiative properties, plant traits and processes. Among these characteristics LAI is the most influential parameter, where higher LAI result in higher energy benefits. Even though, height is not a significant factor plants with lower height provide higher cooling benefits and easy greenery coverage. Increasing of albedo and emissivity can reduce the leaf temperature resulting higher energy benefits. Light colour plants with longer hair length (on pubescent leaves) are more effective in creating cooling effect. Plant with lesser leaf thickness are more beneficial because of the higher heat dissipation and lower heat storage. Plants with higher stomatal conductance helps to maintain lower leaf temperature resulting higher energy benefits. Proper consideration of these plant characteristics will help to enhance the energy performance of VGS. Apart from these plant characteristics there are number of other factors that need to be considered as well. The type of VGS is a key factor, since supporting structure and soil depth differs in each system. In addition, selection of plant species impact on the visual appearance of VGS, fire safety and maintenance requirements. Moreover, selected plant species should be suitable with the local microclimate and environmental conditions to ensure the long-term stability of the system.

6. Conclusion

This study shows that certain plant species have higher potential in providing energy benefits. Therefore, plants with beneficial characteristics need to be selected for VGS. Structural parameters including LAI and plant height are the easily observable plant characteristics. LAI is considered as the most influential plant characteristic affecting thermal performance of VGS. Results show that the increase of LAI from 1 to 5, could reduce the peak exterior surface temperature from 12 ºC, sensible heat transfer from 48 W/m^2 and latent heat transfer from 40 W/m^2 on a hot summer day. Furthermore, the annual cooling load reduction increased from 1.4 %. These results show that plant species with higher LAI, significantly enhance the energy benefits through VGS. The increase of height from 0.05 m to 0.4 m resulted in decrease in the monthly peak cooling load reduction from 0.6 kWh/m^2 and reduction of annual cooling load benefits from 0.09 %. According to these results lower heights showed higher thermal benefits even though the effect is not substantial. On the other hand, one should also consider type of VGS, design goals of the VGS, fire safety, maintenance requirements and environment conditions when selecting plant species as explained in the paper. It should be noted that these findings are subjected to the climatic condition and building properties. Therefore, it is recommended to take deeper consideration of plant choice compatible with building design and local climate to maximize the greenery benefits. Moreover, building and urban planning policies also need to be considered. Once the plant species are properly selected, the steadiness of the system will be ensured while enhancing the environmental and energy benefits.

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