Plant Parameters Influencing the Cooling Performance of Vegetated Roofs: A review

Yee Choong Wong [*], Kok-Yong Chin [**]

[*] Department of Architecture and Sustainable Design (DASD), Universiti Tunku Abdul Rahman, 43000 Kajang, Selangor, Malaysia
[**] Department of Pharmocology, Faculty of Medicine, Universiti Kebangsaan Malaysia

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Abstract **-** High indoor and outdoor temperatures are subjects of concern across the globe. Studies have proven that roofs are the primary component contributing to overheating inside buildings due its maximum solar exposure. This paper reviews plant parameters that could influence the cooling performance of vegetated roofs by studying various typologies. Eight key plant parameters influencing the cooling performance of vegetated roofs have been identified: shading effect of plants, leaf area index LAI, plant evapotranspiration, species selection, plant form, plant physiology, albedo and colour. Studies reveal that shielding effects of plants play a major role in reducing heat gained by roof structures. The presence of dense plants foliage (matured plants with high LAI) creates great magnitude of shadow effects and reduces reflective solar radiation received by building envelope. It is worth noting that rough leaf provides more space on its surface; thus offer better cooling performance. In addition, plant species appear to have different degree of reflectivity; the dark-coloured leaf absorbs the most sunlight energy while light-coloured leaf reflects excess sunlight back to the atmosphere. Hence, roof integrated with dark-coloured plants will be much cooler in comparison. These parameters provide basic source of information with regards to plants selection and integration strategies to be considered when integrating plants on roof for optimum cooling performance.

Keywords - Plant Parameters; Vegetated Roofs; Cooling Performance; Leaf Area Index, Air Temperature Reduction.

I. Introduction

The effects of deforestation and rapid urbanisation have led to many climate-related problems such as higher temperature in urban and rural areas worldwide. Heat has negative impacts on occupants' health. Extreme heat induces excessive loss of body fluid and dysregulation of body temperature, resulting in heat-stroke and death. One of the most significant impacts associated with heat gain issues is the indoor temperature that is outside the range of thermal comfort [2].

Roofs represent the most important source of heat received by buildings in hot and humid regions; it contributes about 70% of the overall heat gain. Many researchers have concluded that rooftop greening could mitigate heat problems. Its benefits have been widely recognized, including indoor air temperature reduction, energy savings, reduced urban heat-island effects and health enhancement. Essentially, plants can act as biofilter to improve air quality by trapping airborne particles through their leaf surfaces and absorb atmospheric gaseous pollutants from the surroundings [1].

The main objective of this research is to investigate plant parameters influencing the cooling performance of vegetated roofs. This paper is organised into several sections. Section II highlights the typologies of vegetated roofs adopted worldwide. Section III discusses the various plant parameters that could influence the cooling performance of vegetated roofs. Section IV presents the limitations of implementing vegetated roofs. The final conclusions are highlighted in Section V.

II. Typology of Vegetated Roofs

The passive cooling of vegetated roofs could be defined in many ways. There are few types of vegetated roofs that are commonly used in buildings. The typical vegetated roofs is composed of few basic components including layered substrate that cover the floor of rooftops with a drainage layer for draining water off the roof and a filter fabric [4].

Modern vegetated roofs were first introduced in Germany in 1880. Vegetated roofs or better known as 'green roofs refer to technology that is established on rooftops for the growth of vegetation. Various environmental and social benefits associated with rooftops greening have been widely recognized include air and noise pollution abatement, storm water management, thermal reduction, energy savings, urban heat island mitigation, human health promotion, and agriculture production and recreational opportunities to the dwellers. Vegetated roofs are usually composed of layered materials to accommodate plants growth [5]. Vegetated roofs systems could be classified into two main types as shown in Table 1.

Table 1 Typology of Vegetated Roofs Systems

Extensive type	Intensive type
• Thickness of soil 3-6 inches (5-15cm) • Lighter: 15-50 lbs/sq. ft. • Lesser plant choice • Lesser maintenance • Cannot be walked on • Lower cost of installation	• Thickness of soil 6 inches or thicker (> 30cm) • Heavier: up to 150 lbs/sq. ft. • More plant choice , can accommodate trees • Accessible as garden • Higher maintenance • Higher cost of installation
	Source: INC, 2015

Fig. 1 Intensive vegetated roof in Malaysia. Source: Author

Apart from these systems, vegetated roofs could also be constructed with various design features as highlighted below:

i. Green cloak – suspended trellises covered with vine plant and climbing plants. Green clock does not add extra weight to building structure compared to typical vegetated roofs. A previous study indicated that it could reduce the indoor temperature in Maryland in July to the extent of 3.1oC [6].

ii. Vegetated trellises – made of simple timber structure, cable and rope wire could cool the roof and ground surface which lead to building cooling by providing bio-shade through the climbing plants [7]. By observing Fig. 2 and Fig. 3, the importance of shading created by plants leaves can be seen. The room behind shaded by the vegetated trellises has significantly lowered the indoor temperature compared to the unshaded one.

Fig. 2 Climbing plants grown around trellis system as a roof canopy for the house. Source: Author

Fig. 3 Vegetated trellises provide shade for the wall of the rooms. Source: Author

III. Plant Parameters Influencing the Cooling Performance of Vegetated Roofs

A. Plant's Shading Effect and Leaf Area Index (LAI)

One of the main plant parameters that show significant cooling effects of vegetated roofs is the shading effects provided by plants. Plants are proven to be effective in cooling buildings by altering the heat energy absorbed. The amount of heat absorbed by roof structure is determined by the shielding effects of vegetated roofs due to presence of plants foliage. The vegetation foliage could act as a natural device to shade building. Essentially, the vegetative ground cover surrounding a building could reduce reflective solar radiation as well as long wave radiation heat gain received by the buildings. Study has proven that air conditioning unit compressor that is placed around plants will reduce ambient temperature and improve COP (co-efficient of performance), thereby consuming less energy [8].

Deciduous plants could be grown over trellises and pergolas assembling a control shading device system to block low sun angles from west (Fig. 4). Vegetated shading devices and awnings could provide deep shade with the use of natural ventilation to bring in fresh air [9]. Research has proven that a shaded site provides 0.64 – 2.52°C lower air temperature, 3.28 – 8.07°C lower surface-soil temperature in comparison with an unshaded area [10].

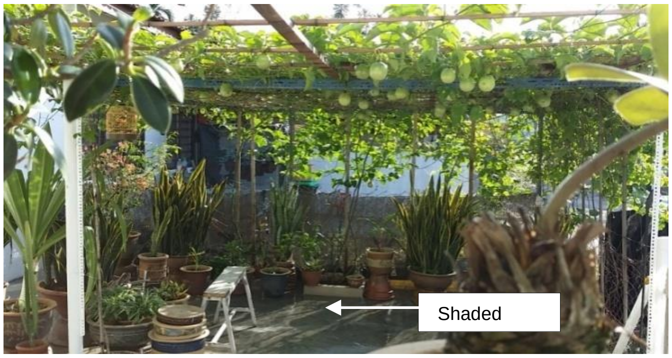

Fig. 4 Vegetated trellises grown climbing plants as a roof canopy to reduce solar energy collected by the ground surface. Source: Author

When integrating vegetated roofs, leaf area index (LAI) should be considered to gain maximum cooling effects. Leaf area index (LAI) is defined as the ratio of leaf area per unit roof surface area (LAI = m2 / m2) that characterizes plant canopies. Essentially, LAI accounts for several plant parameters : thickness of plant layer, age, foliage density and leaf dimension [9]. For instance, the ratio of 0.15 (15% surface coverage with plants) is the loose foliage that not fully cover the surface and the ratio that is close to 1.0 (100% surface coverage with plants) is the dense foliage, usually matured plants (see Fig. 5).

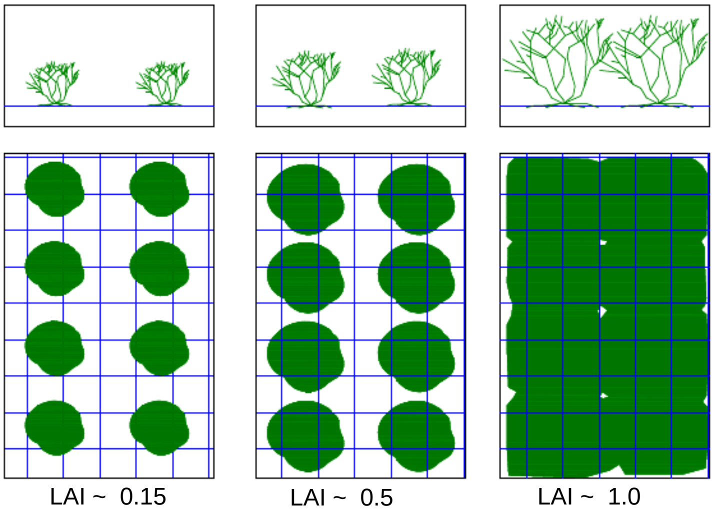

Fig. 5 Leaf Area Index (LAI) mapping of plants grow around trellis system. Source: Author

Nevertheless, plants with LAI < 1 may offer more shades compared to those of higher values as some plants do have overlapping leaves and sections of stems with no leaf cover, hence LAI -1 is not equal to uniform leaf coverage on roof surface [9].

The shadow of the leaves not only blocks incoming sunlight but also dissipates the heat by wind passing over the leaves themselves. The smaller leaves stay cooler than bigger leaves, due to the fact that air movement around them is greater [11, 12]. Leaves could provide shade as well as dispense the heat striking them. It is worth noting that many smaller leaves are more effective than a few large leaves; the size and shape of leaves are also a factor in determining the rate of heat dissipation [13].

Furthermore, plants shading could reduce heat gain and cooling loads by minimizing heat transfer through exterior walls. These will save energy and peak electricity demand. However, plants shading does not play a role at night, cloudy days and roof that shaded by objects [14, 15]. A research reported that indoor air temperature has decreased for about 3°C for a roof shaded by a tree [16].

Shading plays a significant role in plants cooling. The effectiveness of cooling depends on the high volume of foliage. Street trees, for example, have cooling effects of about 100m off their canopy [17]. Plants will absorb solar irradiance and convert it to photochemical energy; some of it will be reflected back as infrared radiation. About 40% - 60% of irradiance leaf captures could still be lost as heat, depending on plant species and environmental influences [18].

B. Plant Evapotranspiration

Plants prevent themselves from overheating in the sun by a process called 'evapotranspiration' – the leaf transpires (i.e. breathes) moisture to its surface, which then evaporates. In the plants physiological process, a small portion of solar radiation is used for photosynthesis, the rest for evaporation of water. This process helps to regulate temperature. Transpiration and evapotranspiration from plants and soil could reduce ambient air temperature. Plants evapotranspiration could increase ambient moisture, thereby increasing indoor humidity. Plants foliage facilitates carbon dioxide intake and release oxygen in the transpiration process [19]. In the process of evapotranspiration; plants evaporate water to the air through leaf surfaces. Evapotranspiration happens through stomatas, microscopic pores on leaf surfaces. Stomatas play a role in controlling water loss of plants as well as controlling gas exchange between leaf and the atmosphere. The leaf evapotranspiration rate is regulated by stomatas' aperture, depending on several factors: air temperature, relative humidity, light levels, water potential between atmosphere and leaf and carbon dioxide concentration of leaf externally and internally. Stomatas open in the day and close at night as they react to ambient light levels. Thus, evapotranspiration would not happen at night [19].

The cooling process through evapotranspiration often occurs on the surrounding foliage and ambient air. Evapotranspirational cooling rate relies on environmental conditions and physiological characteristics of the plants, which include the density and size of stomata pores (resistance and conductance) and leaf area index [14, 15]. Placing plant layer close to air intake of mechanical system has potential in evapotranspirational cooling; the pre-cooled ambient air by plants save air-conditioning energy to achieve desire cooling temperature. Evapotranspiration cools air and humidifies air around the vegetation layer. Plant's cooling could replace the energy consumed in air-conditioning. Hence, the building's carbon budget could be off-set through bio-cooling as well [20]. In the evaporation process, sunlight exits water molecules of leaf, transforming it from liquid to vapour. The water molecules could hold huge amount of energy from escaping as heat [21]. Plants produce large amount of moisture content to dry indoor environment. The evaporation of water from plants is expected to cool building. One m3 of space consumes 680 kWh water evaporated [22].

A hydrated plant will have 100% relative humidity. When water content is low in the atmosphere, a gradient is created to move water out of plant. If the relative humidity is high in atmosphere, driving force for transpiration will be reduced. When all moisture cannot be held, dew will be formed in condensation. Warmer air holds more water by creating larger driving force to move water out from plants though increased transpiration rates. When atmosphere becomes drier, driving force for water movement from plants will become larger; the transpiration rates will also increase. When the plants have higher water content, the absorbance of visible radiation will also become higher [23].

Koyama (2013) concluded that transpiring plants will convert incoming solar radiation to latent energy while dissipating, and cause no increment in temperature [24]. Therefore, evapotranspirational cooling of plants is an effective way to consume heat and does not warm up the surrounding surfaces [25].

C. Plant Species Selection, Plant Form and Plant Physiology

The performance of vegetated roofs depends on the selected plant species. Different species would have different cooling capacity. In plants selection, plants form and physiology should be taken into account to gain maximum cooling. The cooling potential of vegetated roofs is also influenced by other factors such as moisture content of soil. In fact, plants provide cooling through a few mechanisms: air flow modification, providing insulation layers of stagnant air within envelope, short-wave irradiance absorption and conversion to biomass and alteration of the fraction of solar energy reflected from ground into space. All these cooling mechanisms have relative contributions that are reliant on plant form, species, moisture availability, canopy cover, plant vigour and seasonality [9].

According to Friedman (2008), cooling performance of plants are influenced by:

1. Leaf thickness
2. Leaf texture (Rough leaf offers greatest cooling benefits)
3. Foliage density (Dense foliage blocks the ground from collecting energy)
4. Leaf colour lightness [21]

The plant species have different degree of reflectivity. Dark coloured leaf absorbs the most sunlight energy while light coloured leaf reflects excess sunlight back to the atmosphere [21]:

The earth is warmed by the sun when it absorbs waves transferred via sunlight. As plants receive sunlight, the energy excites atoms in leaf. It triggers photosynthesis followed by heat creation. Insufficient heat would result slow growth in plants. In contrast, too much heat would destruct the temperature sensitive molecules of the plants. The ambient temperature remains cooler for the shaded ground as it does not collect energy. Hence, the shaded areas would not release heat during nighttime [21].

Additionally, smooth leaf surface has lesser surface area compared to rough leaf. Rough leaf provides more space across its surface; its leaf offers greater cooling benefits due to high humidity [21]. Vegetated roofs have shadow effects where the magnitude effect relies on the density of foliage [22]. Vegetated roofs with increased density of plants in Mediterranean climate was reported to have reduced cooling load of about 60% compared to a well-insulated bare roof structure of U-value 0.24 W/m2K [26].

D. Albedo and Colour

Vegetated roofs are commonly used to control solar radiation by increasing the surface albedo values with plants cover. Effectiveness of vegetated roofs albedo is dependent on the percentage of green spaces coverage on its surface [27].Vegetated roofs reduce heat flux via roof, shielding the surface from direct solar radiation and the effects of evaporative cooling, generating natural cold air and prevents heat from entering the building by creating an insulation layer [16].

It was reported that vegetated roofs lowered the ambient air temperature by 1°C - 4.3°C in many cities. A well-covered green roof could block up to 60% heat in a building and glare reductions compared to a bare concrete roof. Vegetation provides insulation for reducing cooling and heating costs. In hot summer, rooftop temperature of Chicago's City Hall temperature was measured to be 10°C cooler than the adjacent tar roof [28].

A Malaysian home owner of wooden house that was almost fully covered with vegetation claimed that the vegetation has made their home as cool as if it were air conditioned. The creepers overrun the entire house has also increased structural integrity of the wooden house after its walls coming apart and began to rot [25].The solar energy heats the house is often associated with the surface albedo, when the reflectance of roof is low, more energy is kept to heat up the indoor environment [29].High albedo could lower down the absorbance and heat accrual in roof. The surface temperature will be reduced which corresponds to lower sensible heat fluxes and higher mitigation potential [23].

The layers of material in terms of colour and structure that we use are chosen to control the radiant heat and light entering the building. Some materials will block or reflect heat, others, light. Leaves with higher water content will be more effective to block the heat as they absorb more energy than dry-leafed plants [23]. Pale-coloured leaf reflects more energy and large canopy size provides better shades. Thicker leaves re-emit and store more heat [7]. The temperature of thick dark green roof surfaces is almost 10°C lower than areas covered by sparse vegetation [23].

IV. Limitations in Implementing Vegetated Roofs

Despite all the beneficial factors, there are some limitations in implementing vegetated roofs. A study on the obstacles to implement vegetated roofs in Malaysia showed that vegetated roofs are not popular mainly due to the fact that they are difficult to construct and laborious to maintain. Many people have a perception that vegetated roofs are expensive to install due to limited materials supply and local experts [30].

V. Conclusions

Vegetated roofs have positive contributions to indoor comfort and cooling energy requirements in comparison to the conventional buildings. The use of plants to shade buildings is an effective passive strategy of solar heat control. The cooling performance of vegetated roofs are influenced by plants parameters, including shading effects of plants, plants evapotranspiration, plants form, plants physiology, species selection, roof surface albedo and roof colour. Roof grown with plants tends to be cooler compared to bare surfaces. Furthermore, the heat-island effect is also reduced because the hot air released by the hard surfaces is replaced by fresh air supplied by the vertical mixing of vegetated roofs. These parameters could provide a guide to the architects, landscapers, developers as well as the end users for better integration of vegetated roofs in the built environment. Research to improve applications and practices of vegetated roofs will continue to enhance its overall cooling performance.

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AUTHORS

First Author – Yee Choong Wong, Department of Architecture and Sustainable Design (DASD),Universiti Tunku Abdul Rahman, 43000 Kajang, Selangor, Malaysia

Second Author – Kok-Yong Chin, Department of Pharmocology, Faculty of Medicine, Universiti Kebangsaan Malaysia

Correspondence Author – Yee Choong Wong, Department of Architecture and Sustainable Design (DASD),Universiti Tunku Abdul Rahman, 43000 Kajang, Selangor, Malaysia
E-mail address: ycwong82@gmail.com (Yee Choong Wong)