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Evaluating the thermal reduction effect of plant layers on rooftops

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Abstract

This study examines the thermal reduction effect of plant layers on rooftops through experiments performed in a controlled environment. The relevant parameters are coverage ratio (CR) and total leaf thickness (TLT). Both parameters are positively correlated with thermal reduction ratio (TRR). The TRR data of all experiments were plotted on a grid system with CR on the *x*-axis and TLT on the *y*-axis. A TRR map was then drawn using the curve fitting process. The applicability of the TRR map drawn for *Codiaeum variegatum* (1) was further confirmed by performing experiments with *Cordyline terminalis* (1) and *Ixora duffii* (1) and by results of experiments on *C. variegatum* (2), *C. terminalis* (2), *Duranta repens*, and *I. duffii* (2) in outdoor environments. The TRR map provides quantitative and straightforward guidance on thermal reduction planting arrangements for green roofs.

Keywords: Cooling; Green roof; Heat insulation; Shading

1. Introduction

Intense solar radiation in the tropics and subtropics amplifies the thermal load of buildings, and thereby increases the costs of air conditioning. Researchers have proposed planting trees [1], green roofs [2] or ivy walls [3] around buildings to reduce the thermal load of buildings and urban heat islands by exploiting the biological and physical functions of plants.

Researchers confer that leaf area [4–6] and foliage height thickness (vertical thickness of canopy) [6] are the important factors governing the thermal reduction effect of plant layers on rooftops. Wong et al. [4] mentioned that the thermal reduction effect of green roofs increases with the leaf area index (LAI). However, that investigation did not quantify the relationship between LAI and the thermal reduction effect. Del Barrio [5] presented a mathematical model of the cooling effect of canopies. Barrio's work reveals that LAI is negatively correlated with transmitted solar flux. However, this model comprises 18 parameters that cannot be easily determined by environmental designers. The model was too complicated and could not be applied on a large scale by laymen. Kumar and Kaushik [6] examined an energy balance model for green roofs and confirmed their experiments in the field. They demonstrated that the LAI and foliage height thickness are negatively correlated with heat flux. However, the energy balance model employs 20 parameters, and is therefore too complex. The model includes foliage height thickness as a parameter. While tree canopies may have similar vertical thickness, the number and thickness of leaves of different plant species can vary. Consequently, the thermal reduction effects of various species are not necessarily similar. In conclusion, a model of thermal reduction effect from plant layers on rooftops has been proposed, but the canopy form parameter requires further clarification. It is thus very important to explain the parameter of the canopy form for thermal reduction, and construct a simple and convenient model for thermal reduction by plant layers on rooftops.

This study examines the thermal reduction effect of plant layers on rooftops. The parameters are coverage ratio and total leaf thickness. Maps showing thermal reduction ratio were constructed based on coverage ratio and total leaf thickness. The maps provide a tool to quantitatively and plainly elucidate the thermal reduction effect of plant layers on rooftops.

2. Materials and methods

2.1. Materials

The plants employed in this study are commonly used as ornamentals in the tropics and subtropics. Ornamental species

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Nomenclature

CR	coverage ratio of leaf (%)
LAI	leaf area index
T_A	the atmospheric temperature (°C)
T_P	the temperature of P% coverage ratio (°C)
T_0	the temperature of 0% coverage ratio (°C)
TLT	total leaf thickness, plant layer multiplied by average leaf thickness
TRR	thermal reduction rate (%)

must be vigorous, with many leaves and a large coverage ratio, such that they can exhibit the potential thermal reduction effect on green roofs. First, the plant *Codiaeum variegatum* (1) was tested in a controlled experimental chamber in the lab for the purpose of plotting a thermal reduction map of this plant species. Second, the same experiment was conducted with *Cordyline terminalis* (1) and *Ixora duffii* (1) to verify the map. At last, four plant species *C. variegatum* (2), *C. terminalis* (2), *Duranta repens* and *I. duffii* (2) were tested in outdoor settings to verify the applicability of the TRR map. Table 1 presents the species and characteristics of the experiment.

2.2. Parameters

The parameters adopted herein are the coverage ratio and the total leaf thickness. Methods of estimation are explained below.

Measuring leaf coverage ratio (*CR*). This research used 8 white nylon threads to divide the growing areas into 25 grids 8 cm × 8 cm. The tested plant was later put into a grid and was held straight by the nylon threads. The leaf coverage ratio (%) was calculated by dividing the total number of grids covered by the tested plants by the total number of grids (25).

Measuring total leaf thickness (*TLT*). First, 10 leaves were randomly chosen and their thicknesses were measured using a micrometer to determine average leaf thickness. Second, the mean number of plant layers was estimated, and the average leaf thickness was multiplied by the average number of layers to yield TLT.

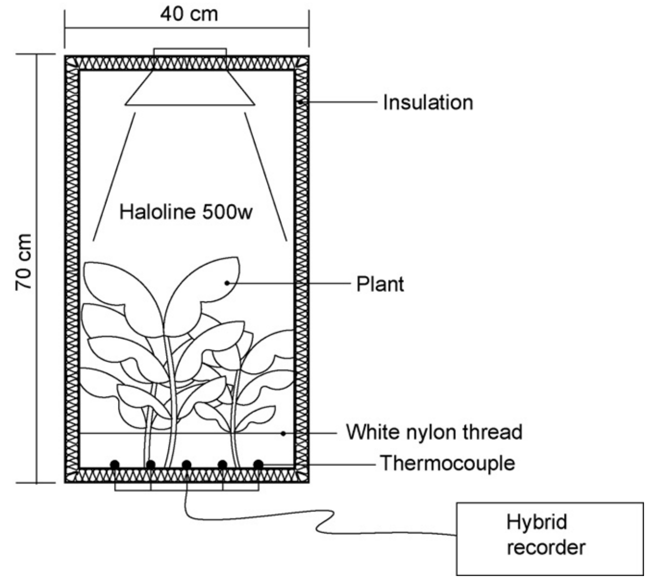

Fig. 1. Indoor measuring system.

2.3. Experimental system

This study comprises two experiments. The first experiment was set up indoors in a chamber with a stable light source. The plants were placed in the chamber and their thermal reduction effect was measured. The atmosphere was controlled so that the influence of background temperature, moisture and wind velocity could be excluded, simplifying the factors involved and supporting a discussion of the main factors. The second experiment was performed outdoors. Four species of plants were planted in pots on rooftops to confirm the data from the first experiment.

2.3.1. Indoor experiment

The chamber ($L \times W \times H$: 40 cm × 40 cm × 70 cm) was established and covered with heat insulation to prevent interference from atmospheric temperature and light (Fig. 1). The indoor temperature was maintained at 28 ± 0.5 °C. A light (OSRAM HALOPIN: 500 W) was placed on the top of the chamber to provide thermal energy. A black plastic board lay on the bottom of the chamber. Five thermocouples (K-type) were placed on the plastic board and connected to a hybrid recorder.

Table 1
Characteristics of plants used in the experiment

Experiment type	Characteristics of plants			Experimental status		
	Species of plant	Average thickness per leaf (mm)	Plant height (cm)	Coverage ratio of plant (%)	Layer of plant	Background temperature (°C)
Indoor experiment	*Codiaeum variegatum* cv. 'Indian Blanket' (1)	0.45 ± 0.04S.E.	60	100, 80, 60, 40, 20	1–7	28
	Cordyline terminalis cv. 'Aichiaka' (1)	0.23 ± 0.005S.E.	75	100, 80, 60, 20	5, 8	28.2
	Ixora duffii cv. 'Super King' (1)	0.35 ± 0.011S.E.	65	100, 80, 40, 20	1, 4, 6, 8	28.5
Outdoor experiment	*C. variegatum* cv. 'Indian Blanket' (2)	0.45 ± 0.04S.E.	60	70	6	25.6
	C. terminalis cv. 'Aichiaka' (2)	0.23 ± 0.005S.E.	70	50	6	26
	Duranta repens cv. 'Golden Leaves'	0.27 ± 0.014S.E.	50	100	5	24.1
	I. duffii cv. 'Super King' (2)	0.35 ± 0.011S.E.	70	90	8	29.6