Ecological Indicators 128 (2021) 107816

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Modelling of vertical greenery system with selected tropical plants in urban context to appraise plant thermal performance

T.A.N.T. Perera [a,b], G.Y. Jayasinghe [a,c,*], R.U. Halwatura [d], H.T. Rupasinghe [d]

[a] Department of Agricultural Engineering, Faculty of Agriculture, University of Ruhuna, Mapalana, Kamburupitiya, Sri Lanka
[b] Department of Environmental Technology, Faculty of Technology, University of Colombo, Colombo, Sri Lanka
[c] Melbourne School of Land and Environment, The University of Melbourne, 500Yarra Boulevard, Richmond 3121, Australia
[d] Department of Civil Engineering, Faculty of Engineering, University of Moratuwa, Moratuwa, Sri Lanka

ARTICLE INFO

Keywords:
ENVI-met
Leaf Area Index
Mean temperature difference
Plant physiological parameters
Urban microclimate

ABSTRACT

Different growth parameters and thermal performances of selected plant species grown on vertical system modules in urban tropical climate have been investigated under the study. Further, outdoor thermal comfort simulation has been modeled by ENVI-met 4.4.5 to investigate the applicability of selected plant species in three different tropical conditions (Colombo Sethsiripaya administrative complex, Matara urban council building and Kandy Urban council building). Sample modular vertical green living wall panels were fabricated by using timber frames (60 × 40 × 5 cm) packed with cocopeat medium with a depth of 3.8 cm. Nine plant species; such as *Desmodium triflorum*, *Roheo spathacea*, *Centella asiatica*, *Axonopus fissifoliu*, *Axonopus compressus*, *Elusine indica*, *Dieffenbachiae spp*, *Tectaria spp*, and *Bigonia spp* were selected for the study. Plant survival percentages, plant height and leaf area index (LAI) were recorded for 8 weeks. Thermal performances were evaluated by considering temperatures at (a) 20 cm distance in front of the green wall, (b) substrate surface of the green wall modules and (c) inside the green wall compared to (d) adjacent bare wall (Control). The highest LAI was recorded from *Roheo spp* (3.99) followed by *Axonopus f.* (3.20) and *Elusine spp* (2.21). *Axonopus f.* exhibited the highest coverage on the living wall due to high LAI (>1). The highest temperature reduction (5.06 °C) was displayed by *Axonopus f.* compared to the other species as it covers large extent of the wall. The simulation study of the green walls developed with *Axonopus f.* signified a possible maximum temperature reduction of 2.07 °C, 3.29 °C and 2.03 °C in Colombo Sethsiripaya administrative complex, Matara urban council building and Kandy urban council building, respectively. Hence, modelling vertical greening with *Axonopus f.* can effectively enhance the thermal performance in urban context due to their LAI values and the thermal performances.

1. Introduction

As a critical factor of earth ecosystems, vegetation plays a major role in mitigating climate change. Inserting vegetation to the urban environment will enable metropolitan areas become more comfortable, cooler and unobtrusive (Morabito et al., 2020; Xu et al., 2018). Green walls offer very significant social, environmental and economic benefits such as mitigating Urban Heat Island (UHI) effect, reducing energy related carbon dioxide emissions (over air conditioners), advance citizens' wellbeing and productivity (aesthetic and noise control), and providing habitat for organisms (Liu et al., 2019; Ulpiani, 2020).

The demand for green living walls is escalating expeditiously due to the benefits that they offer and the aim is to improve existing wall systems with vegetation (Sharma et al., 2016). High density plantings can be established through intensive management and by using modular green living walls (Perkins and Joyce, 2012). Vegetation can help to diminish the urban heat island (UHI) effect by masking the surfaces of buildings by plants, deflecting radiation from the sun, and releasing moisture into the atmosphere (Manso and Castro, 2015; Pan and Kao, 2021). Embedding vegetation on walls similarly increases evapotranspiration and it can support to reduce heat accumulation in buildings (Flatbud, 2017; Jillian, 2016). Most green living walls are complex configurations that are having supportive structures with different attachments (Anderson, 2016; Mazzali et al., 2013). An impermeable assistance is required to separate the green living wall from the building in order to evade complications associated with moisture. Different

* Corresponding author at: Department of Agricultural Engineering, Faculty of Agriculture, University of Ruhuna, Mapalana, Kamburupitiya, Sri Lanka.
E-mail address: jayasinghe@ageng.ruh.ac.lk (G.Y. Jayasinghe).

https://doi.org/10.1016/j.ecolind.2021.107816
Received 8 January 2021; Received in revised form 2 May 2021; Accepted 19 May 2021
Available online 26 May 2021

supportive structures can be used in vertical green living walls as double skin envelops (Manso and Castro, 2015; Perini and Rosasco, 2013). This is creating an air gap between building wall and the living wall and improves subsequent ventilation (Sheweka and Mohamed, 2012). An irrigation system is indispensable for watering and fertigation practices (Charoenkit and Yiemwattana, 2016). Both organic and inorganic substrates (soilless or hydroponics) along with mineral nutrients can be used to grow plants on vertical greenery systems, (Anderson, 2016). In addition, variable materials, structures and wide variety of plant species have been using in green living walls (Rizwan et al., 2008). Initially, epiphytic plants grown in tropical rain forests were used in green living walls. With the time, it has been found that a wide range of plant species have the potential of been used and raised properly on vertical green living walls (Weerakkody et al., 2017). Epiphytes, lithophytes (growing on other plants and on rocks by deriving nutrition from atmosphere) ferns, succulents, shrubs, and herbaceous or climbing plants are the different types of plants that can be used in green living walls (Chen et al., 2013).

Plant species which can be used for green living walls vary according to microclimatic conditions (sun exposure, wind exposure, height) (Mazzali et al., 2013) and its aesthetic values and gardening structures around the building (Chen et al., 2020; Koyama et al., 2013; Pérez et al., 2017). Therefore, selecting the best suitable plant species for green living walls is a key aspect to achieve maximum thermal comfort in the building. As vegetation coverage can be estimated according to the leaf area indices and plant height in green living walls, this study will appraise the plant thermal performances through LAI and plant height. Further, as a preliminary study, it will assess the possibility to alleviate the UHI through precise plant installation by computer simulation with the adaptive use of a numerical simulation model software known as ENVI-met (LEONARDO) (Galagoda et al., 2018; Herath et al., 2017; Perera et al., 2021). The ENVI-met model is one of the most commonly used dynamic simulation tools for microclimate modeling. ENVI-met measures the microclimate and air quality in metropolitan areas and its physical fundamentals are based on fluid mechanics and thermodynamics (Tsoka et al., 2018).

A number of European researchers have studied green living wall systems (Irga et al., 2017; Masi et al., 2016) and information about their positive effects and novel trends are available (Alexandri and Phil, 2008; Marzluff et al., 2008; Malys et al., 2014). But studies in the tropical climate, have not much been conducted. Therefore, the present study was conducted: (a) to select the most suitable plant types to grow on cocopeat medium on vertical green living wall panels (b) to investigate the different plant growth and development parameters (i.e., LAI, average leaf dimensions, and plant growth rates) of the plants and thermal performance (c) to envisage the feasibility of ENVI-met software in different tropical regions with selected green living wall systems.

2. Materials and methodology

2.1. Plant selection study (Phase 01)

2.1.1. Experimental site

The experimental site selected for the research study was the Department of Civil Engineering Faculty of Engineering, University of Moratuwa, Sri Lanka (6.7969°N, 79.9018°E). The green living wall modules were fixed on the front wall of a building of the Department of Civil Engineering as it received direct sunlight during the day and away from environmental impacts and easily accessible. Large cement walls were selected to fix the sample green living wall modules to achieve maximum performances. A 10 cm air space was allowed between the building and the green living wall panel during the installation of green modules on the wall,

2.1.2. Fabrication of the sample green living wall modules

The fabricated modular green living wall system consists of separate parts which can be assembled and planted ex-situ and later fixed into the building wall vertically. Green living wall panels and the frames were prepared by using timber (60 × 40 × 5 cm) and the thickness of the wooden panel was 3.8 cm. Two coatings of wood care sealer were applied with thinner solvent to improve the water resistance and the durability. Each panel was divided into two parts by adding a barrier across the panel horizontally to increase the stability of the green vertical wall,

Cocopeat was used as the growing medium due to its light weight, high water holding capacity and its binding ability (Abad et al., 2002; Awang et al., 2009; Iasiah and Khanif, 2004). The pH, electrical conductivity (EC) and water holding capacity values of selected cocopeat were 5.3, 1.9 dSm^{-1} and 34% (w/w), respectively. Further, cation exchange capacity was 94.6 cmol (c) kg^{-1} and the carbon: nitrogen ratio was 186:1. To be a productive growing medium, it should consist of a good physical structure with the ability to obtain a successful balance between water and air in the medium during and after the irrigation. Cocopeat layer was fixed to the panels by using a wire mesh. Thickness of the substrate layer was 3.8 cm.

2.1.3. Selection of plant types

Selection of plant species has been undertaken according to their growth form, growing medium and their adaptability to the vertical environment. In addition, selected plants can be withstand with shallow soil, high winds, intermittent flooding and drought (Cameron et al., 2014).

Plant selection matrix developed by Perkins and Joyce (2012), was used to analyze the relevance of each plant species to the context of tropical climate. The selection matrices were structured by using a question-and-answer approach where plant species are considered as a) potentially suitable, b) potentially suitable under certain circumstances, c) unsuitable. According to the plant selection matrix, selection criteria for exterior green living walls were generated and applied to 20 tropical plant species to identify at least nine species putatively suited to vertical green living walls in tropical conditions (Fig. 1).

Selected plants for the present study were obtained from plant suppliers and native plant nurseries according to following criteria (Table 1) and all plant types were authenticated by the expert committee of the Royal Botanical Gardens, Peradeniya, Sri Lanka.

2.1.4. Irrigation and fertilizer application

In the early stages of the plants, the panels were irrigated twice a week, early morning (9.00 am) by manual sprayers, until the entire growth medium getting wet. To avoid moisture loss and to retain enough heat, 0.5L of water was applied per each panel. Nutrient supply was not done for the plantlets until they produce true leaves. Therefore, the nutrient supply was gradually started when the leaves unfolded. Nutrient solution was prepared by dissolving 0.5 g of Albert's mixture in 500 mL of water for each panel and applied twice per week. The Albert's solution covers a wide range of nutritional ratios and balanced with high nitrate nitrogen content, was chlorine free and dissolved instantly. Saplings of selected plant species were maintained under control conditions with equal care for each panel during the study period.

2.1.5. Data collection and analysis

Plant growth parameters (plant height, LAI) were measured for two months (Sept - Oct) at a regular interval (Weekly) of the time and September is still receives high temperature (28–30 °C) during the year. The heights of the plant and leaf dimensions were recorded on weekly basis by using a measuring tape. Total 48 leaves were selected from each species and leaf length and the width were measured. Percentages of thrived plants in the green living wall module were measured weekly to assess plant survival rates. Plant survival rate was calculated by counting the number of plants of each species that have survived, divide it by the number of plants originally planted of that species and multiply by 100 to express as a percentage of survival (Macera et al., 2017). Visual

Fig. 1. Selected Plant species for the study a) *Desmodium triflorum*, b) *Roheo spathacea* c) *Centella asiatica*, d) *Axonopus fissifoliu*, e) *Axonopus compressus*, f) *Elusine indica*, g) *Dieffenbachiae* spp, h) *Tectaria* spp, i) *Bigonia* spp.

assessments of pest and disease incidence of the plants were also considered along with the measurements of plant height. LAI was measured according to the method described by Singh et al. (2018). Graph paper method was used to measure the LAI of broad leaf plants and following equation 1 was used to measure the LAI of linear leaf plants (Smith and Smith, 2015).

$$\mathrm{LeafAreaIndex(LAI)} = \frac{\mathrm{LeafArea}}{\mathrm{GroundArea}}$$

The experimental design used in the study was completely randomized design (CRD) with three replicates for each plant species.

2.2. Plant thermal performances assessment (Phase 02)

Six plant species were rejected due to failure in survival during the study period after investigating growth performances. Three plant species were identified as the most appropriate plant types in terms of survival and growth performances. Three prototype modular panels with selected three plant species were fixed to the building wall permitting 10 cm air gap in between building wall and the wooden panel. The selected wall was west facing and directly exposed to the solar radiation and temperature gauging points were determined according to Perini et al. (2011).

Temperature measurements were taken at the internal wall, 20 cm above from the canopy level, substrate surface and in the air gap for each green living wall comparatively to the adjacent bare wall (control). Data collection was carried out during the day time on a clear sunny day by using data logger type Graphtec-midi GL820. Temperature measurement and clock accuracy were 23 °C ± 5 °C and ± 0.002% (approx. 50 s per month), respectively. Measurements were taken for 48 h in 10 min interval time at 1.5 m height from the ground level.

2.3. Simulation study (Phase 03)

According to the plant growth and plant thermal performances study, *Axanopus fissifoliu* was selected as the best suitable plant species for the vertical green living walls in tropical climate.

The effect of *Axanopus fissifoliu* in temperature reduction was examined by modeling a selected building in urban microclimatic context within Sri Lanka. Sri Lanka can be categorized as tropical country as it locates within the tropics between 5° 55′ to 9° 51′ north latitude and between 79° 42′ to 81° 53′ east longitude. The average annual temperature in Sri Lanka is 27.0 °C and the maximum average temperature is 31 °C. Most of the urban cities experiencing excessive day time temperature during a year.

Colombo Sethsiripaya Administrative complex (Fig. 2a), Matara Urban council Building (Fig. 2b) and Kandy Urban council building (Fig. 2c) [Af][1] were the selected locations to represent different agro climatic zones within the country. Further, these locations are highly populated during day time. Sethsiripaya building is a 14 storeyed building made up with concrete walls and concrete slabs located in western province of Sri Lanka. It lies on 14 m above sea level. There is a significant rainfall throughout the year in Colombo (WL_4)[2]. The average annual temperature is 26 °C in Colombo.

Matara urban council is located in southern province Sri Lanka belongs to WL_4. Matara lies on 11 m above sea level. The average annual temperature is 26.8 °C and average annual rainfall is 2147 mm. Matara urban council building was three storeyed made up with concrete and tile walls with terracotta roofing.

[1] The Köppen Climate Classification subtype for Colombo, Matara and Kandy climate are "Af" (Tropical Rainforest Climate).

[2] WL_4 Wet zone Low country

Table 1
Characteristics of selected plant species according to the plant selection matrix.

Plant Species	Root system	Growth Habit	Life cycle	Tolerance to harsh weather	Pest and diseases attack / Deficiencies and toxicities	Effect to human
***Desmodium triflorum* (Fabaceae)**	Shallow root system with woody taproot (Rahman et al., 2012)	Stems are strongly branched up to 50 cm length and frequently rooting at the nodes to form a mat. Creeping mat can provide good ground cover (Ahmad et al., 2011).	Perennial (Singh et al., 2015)	Well adapted to tropical and warm subtropical environments (Rahman et al., 2012).	No any significant information (Wong et al., 1985).	No any harmful effects (Singh, 2015).
***Roheo spathacea* (Commelinaceae)**	Roots regenerate easily when pulled up or broken (Flatbud, 2017).	Evergreen clump forming (Islam Shafrqul et al., 2003). Approximate growing height is 30–40 cm and width 40–50 cm. Blades broadly linear, sharp-tipped, and waxy, stiff forms dense ground cover and form clumps quickly (Ranker and Haufler, 2008).	Perennial (Gilman, 1999)	Drought tolerant. Cultivated widely in the tropics (Gilman, 1999).	Less pest and diseases attack / Deficiencies and toxicities (Gilman, 1999). No any significant information	
***Centella asiatica* (Apiaceae)**	Shallow root system (Liu et al., 2008).	Maximum plant height 0.2 m. Maximum plant spread / crown width is 1 m plant with a creeping growth habit (Flora Fauna Web - Plant Detail - Centella asiatica, 2013)	Evergreen Perennial herb (Liu et al., 2008)	Well adapted (Briargate Botanicals, 2020).	No any significant pest and diseases information (Liu et al., 2008).	Medicinal plant (Islam Shafrqul et al., 2003)
***Axonopus fissifoliu* (Poaceae)**	Shallow-rooted (>90% of roots in the 0–5 cm layer) (Percy, 2000)	Leaf blades 4–6 mm wide and 5–15 cm long. Forms more slender culms and stolon, narrower and shorter leaves. Forms a dense mat with 15–30 cm tall foliage (DEEDI, 2016).	Perennial (Simon and Sharp, 2002)	Drought tolerant (Shouliang and Phillips, 2006).	It is not subjected to any major diseases or insect pests (Jagoe, 1940).	No any significant information.
***Axonopus compressus* (Poaceae)**	Shallow root system (Arunbabu et al., 2015)	Forms a dense mat with foliage 15–20 cm tall. Leaf blades shiny, flat or folded, 4–18 mm wide, and 2–16 cm long, glabrous or hairy on the upper surface. Forming a thick mat (Shouliang and Phillips, 2006).	Perennial (Shouliang and Phillips, 2006)	Withstands to dry weather better (Chin and Board, 2014).	No any significant information	
***Elusine indica* (Poaceae)**	Shallow fibrous root system (Steed et al., 2016)	Growing up to 0.5 m at a fast rate. Prefers well-drained soil (Steed et al., 2016).	Annual / Perennial (Steed et al., 2016)	Tropical and subtropical regions (Steed et al., 2016).		
***Dieffenbachiae* spp (Araceae)**	dumb cane plant (Ortiz and Croat, 2017)	Ranging from small dwarf type varieties to the large dark green mottled foliage. Ability to purify air (Roehrs and Gilman, 1999).	Perennial (Roehrs and Gilman, 1999)	Tropical plant (Roehrs and Gilman, 1999).	Usually not affected by pests (Roehrs and Gilman, 1999)	Can be toxic (Aigbokhan, 2015)
***Bigonia* spp (Begoniaceae)**	Fibrous, tuberous or rhizomatous roots (Phutthai et al., 2012)	Species range in size from a few inches to over 12 feet in height. The leaves are usually asymmetric and often have color variation (Phutthai and Sridith, 2010).	Perennial (Phutthai et al., 2012)	Native to moist subtropical and tropical climates (Maw et al., 2020)	According to previous literature, susceptible than other 8 plant species (Maw et al., 2020; Phutthai and Sridith, 2010).	No any significant information.
***Tectaria* spp (Polypodiaceae)**	Shallow root system (Maw et al., 2020)	Fern. Nonflowering vascular plants that possess true roots, stems, and complex leaves and that reproduce by spores. Always fibrous (Shi-Yong Dong et al., 2017)	Perennial (Patil et al., 2019)	Growing profusely in tropical areas (Patil et al., 2019)	No any significant information.	

Kandy urban council located in central province Sri Lanka (WM_3)[3]. The Kandy lies on 518 m above sea level and has a significant amount of rainfall during the year. The average annual temperature in Kandy is 24.5 °C and annual rainfall 2083 mm. Building was made up with two storeyed and plaster bricks wall with corrugated asbestos roof.

ENVI-met version 4.4.5 was used to create the 3D model of selected buildings with designed green living wall by using *Axanopus fissifoliu* plant spp. Herath et al. (2017), explained that ENVI-met software can be used for micro climatic simulation in tropical context. Therefore, Initial validation of the ENVI-met was done to test the feasibility of applying *Axanopus fissifoliu* by modelling the building in the premises of Civil Engineering Department, University of Moratuwa, Sri Lanka (6.7969°N, 79.9018°E) (Fig. 3).

New data base was created in the software for *Axanopus fissifoliu* to study the green living wall system (Table 2). Temperature variations were monitored by installing two temperature receptors at 1.5 m height. Temperature data were collected for 48 h in ten minutes intervals in warmest day during the study period.

Sethsiripaya administrative complex (Colombo-Fig. 4a1, Matara Urban council Building (Fig. 4b1) and Kandy Urban council building (Fig. 4c1) were modeled to represent existing conditions in the selected sites (Table 3).

Further, selected sites were modeled with vertical green living wall (a_2, b_2, c_2) to compare the temperature reduction with existing conditions (Fig. 4). The used meteorological input data for the study were summarized in the Table 4. Hourly climatic data was collected during a day time on a clear sunny day by using data logger type Graphtec-midi GL820.

In order to maintain the model resolution and to manage computational capacity, small subsections were modeled from each particular built-up area. The models were created with the area input files (bitmap image files) and it was rotated from north direction by different angles (Colombo-a_1 − 20°, Matara Urban council Building (b_1) − 22°, Kandy Urban council building (c_1) − 12° in order to align the grids with the main direction of the roads and constructions. Google earth images were

[3] WM3 Wet zone mid country

Fig. 2. Selected buildings a) Colombo Sethsiripaya b) Matara urban council c) Kandy urban council.

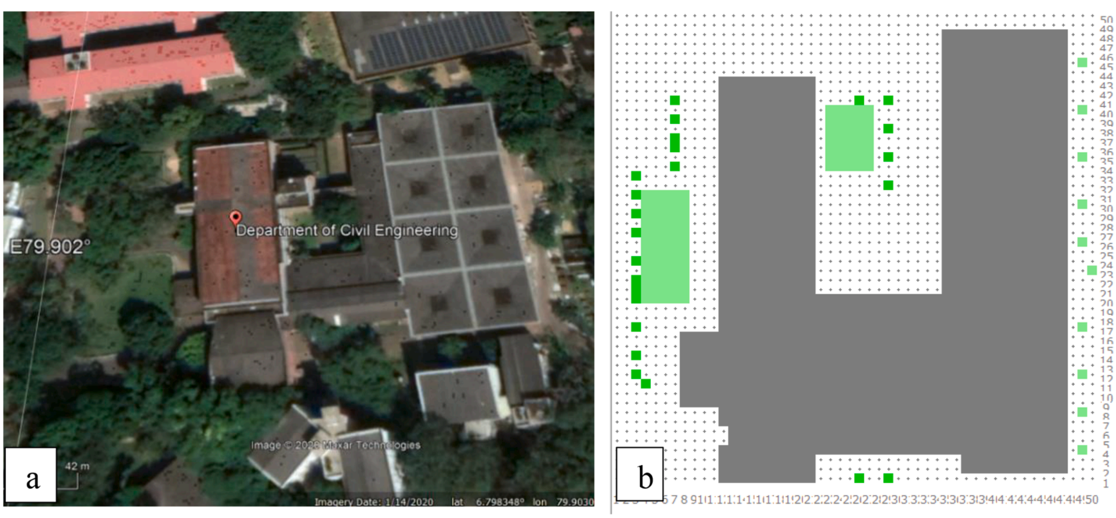

Fig. 3. Calibration Site a) Google earth image b) 2D Model ENVI-met.

Table 2
Created data base for new green living wall system.

Plant type	*Axanopus fissifoliu*
LAI	3.20
Leaf angle distribution	0.7
Plant Thickness (m)	0.2
Substrate layer 1	cocopeat
Substrate layer 1 thickness (m)	0.038
Emissivity substrate layer 1	0.85
Albedo substrate layer 1	0.7
Water coefficient of substrate layer 1 or plant	0.5
Substrate layer 2	Wooden panel
Substrate layer 2 thickness (m)	0.02
Emissivity substrate layer 1	0.95
Albedo substrate layer 1	0.9
Water coefficient of substrate layer 1 or plant	0.5
Air gap between wall and green living wall (m)	0.15

used to model building facades and layout, ground surface and plants. The input domain size was 60 × 60 × 30 (x-y-z) with 5 nesting grids.

3. Results

3.1. Plant selection study (Phase 01)

Plant survival rates over the research study period were 100% for *Elusine indica*, *Axonopus fissifoliu* and *Rhoeo spathacea* species. Reset of the species showed a decreasing survival rate from September to October. *Centella asiatica* displayed a comparatively slow growth rate and was not capable to survive in the vertical environment. *Begonia spp* did not show better growth and survival in vertical situation. *Tectaria* spp and *Desmodium triflorum* displayed a decreasing survival rate during the study period. Eventhough *Dieffenbachia spp* were not survived in the vertical environment, it has indicated that 100% survival rate in the horizontal environment over the trial period with an ideal LAI (2.45).

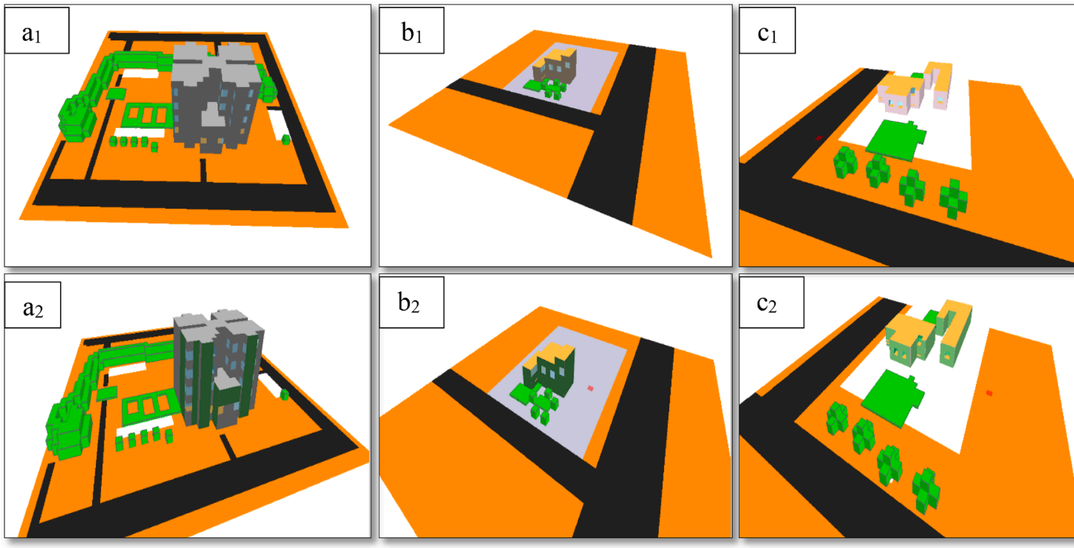

Fig. 4. Models for each sites a_1) Sethsiripaya administrative complex (Colombo), a_2) Sethsiripaya administrative complex with vertical living wall b_1) Matara Urban council Building b_2) Matara Urban council Building with vertical living wall c_1) Kandy Urban council building c_2) Urban council building with vertical living wall.

Table 3
Characteristics of building environment.

Model area	Average height (m)	Roof materials	Roof type	Wall materials	Road materials
Sethsiripaya administrative complex (Colombo)	30	Concrete slab	Flat	plaster block walls	Asphalt, light concrete
Matara Urban council Building	15	concrete slab and terracotta roofing	Flat	concrete and tile walls	Asphalt, light concrete
Kandy Urban council building	12	Corrugated asbestos roof.	Gable	plaster bricks wall	Asphalt, light concrete

Table 4
Details of initialization input parameters for the ENVI-met simulation.

Condition	Colombo	Matara	Kandy
Simulating duration	24 h	24 h	24 h
Start time	1900 h	1900 h	1900 h
Wind speed (m/s)	2.2	5	0.2
Wind direction	270°	270°	270°
RH in 2 m (%)	75	75	75
Specific humidity at model top	9	9	9
Roughness length at the measuring site	0.1	0.1	0.1
Initial temperature	28 °C	28 °C	28 °C

Although some plants showed minor bacterial blight spots on the leaves, plants were consistently heal their during the study period. Plant growth rates of each species varied according to the mean plant height (Fig. 5a) and the LAI (Fig. 5b).

Rhoeo spathacea displayed the highest rate of spreading on the vertical panel surface (Fig. 6). The average height and the mean LAI of the plant during the study period were 8.21 cm and 3.21, respectively.

The slower growth of *Axonopus fissifoliu* maintained a continuous steady rate of spread and it showed a mean plant height of 6.7 cm and the LAI was 3.20 throughout the experimental period. Most of the other trial species in this study reached heights between 10 and 15 cm. *Elusine indica* showed a significant growth in the vertical condition with 8.00 cm average plant height and the LAI of 2.21 when compared to other species.

3.2. Plant thermal performances assessment (Phase 02)

Plant species that showed the best growth performances were selected to the initial study of the thermal performance assessment. Selected plant species were *Rhoeo spathacea, Axonopus fissifoliu* and *Elusine indica.* These plant species were tested with the control wall panels which have no plant species (Bare wall). During the study period mean air temperature varied from 30 °C to 40 °C.

According to Fig. 7a, selected plant species did not show a significant difference ($p < 0.05$) in the mean air temperature 20 cm away from the canopy level when compared to the control (P values of 0.927, 0.934 and 0.493 for *Rhoeo spathacea, Axonopus fissifoliu* and *Elusine indica*, respectively). The difference between bare wall and the green living wall temperature at 20 cm in front of the walls were 0.65◦C for *Rhoeo spathacea*, 0.44◦C for *Axonopus fissifoliu* and 0.54◦C for *Elusine indica,* respectively.

As shown in the Fig. 7b, mean temperature reduction of the substrate surface of *Elusine indica* wall panels were 0.89 °C and it was not significantly different ($P = 0.201$) when compared with the control panel. *Rhoeo spathacea* and *Axonopus fissifoliu* recorded a significant difference ($P = 0.007$, 0.016) compared to control panel. It showed 2.49 °C and 2.78 °C temperature reduction of the walls when compared to the control, respectively.

Mean temperatures of the panel back side recorded at different time intervals for a period of 24 h were significantly different [*Rhoeo spathacea*, (0.002), *Axonopus fissifoliu* (0.000), *Elusine indica* (0.019)] among the species. Maximum temperature reduction of panel back side in *Rhoeo spathacea*, *Axonopus fissifoliu* and *Elusine indica* were 5.06 °C, 3.85 °C and 2.93 °C, respectively compared to control. The highest temperature reduction of 5.06 °C was recorded by the green living wall panel with *Axonopus fissifoliu* when compared to other species and the control (Fig. 7c).

Different plant species showed different temperature reductions behind the panels according to Fig. 8. Among selected three species the highest temperature gradient through the wall was indicated by the *Axonopus fissifoliu.*

3.3. Simulation study (Phase 03)

Outdoor thermal environmental variations by incorporating a green

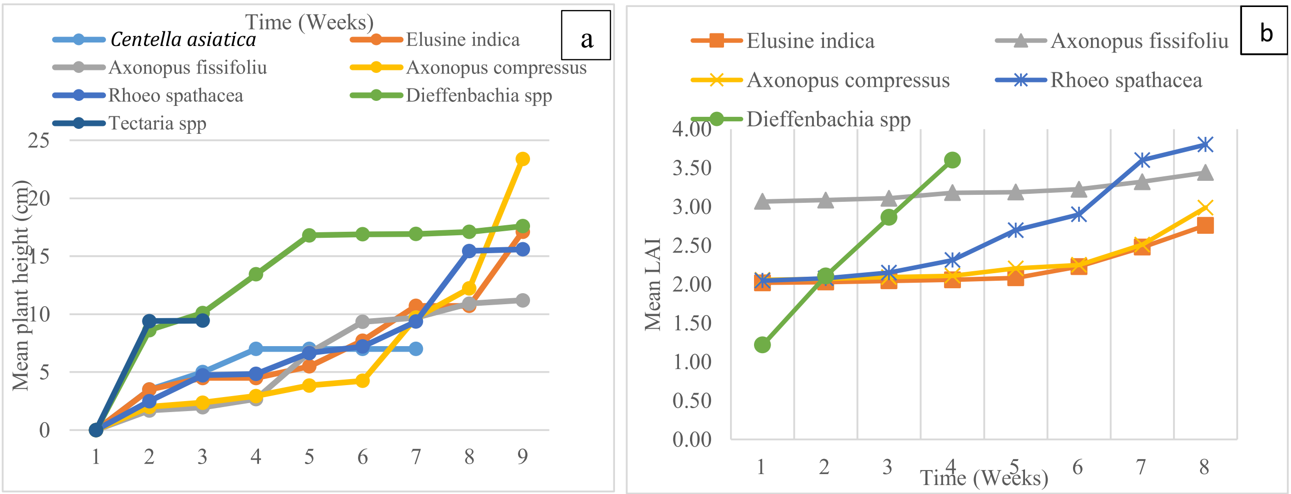

Fig. 5. Variations in plant growth parameters off selected plant species a) Mean plant height b) Mean LAI.

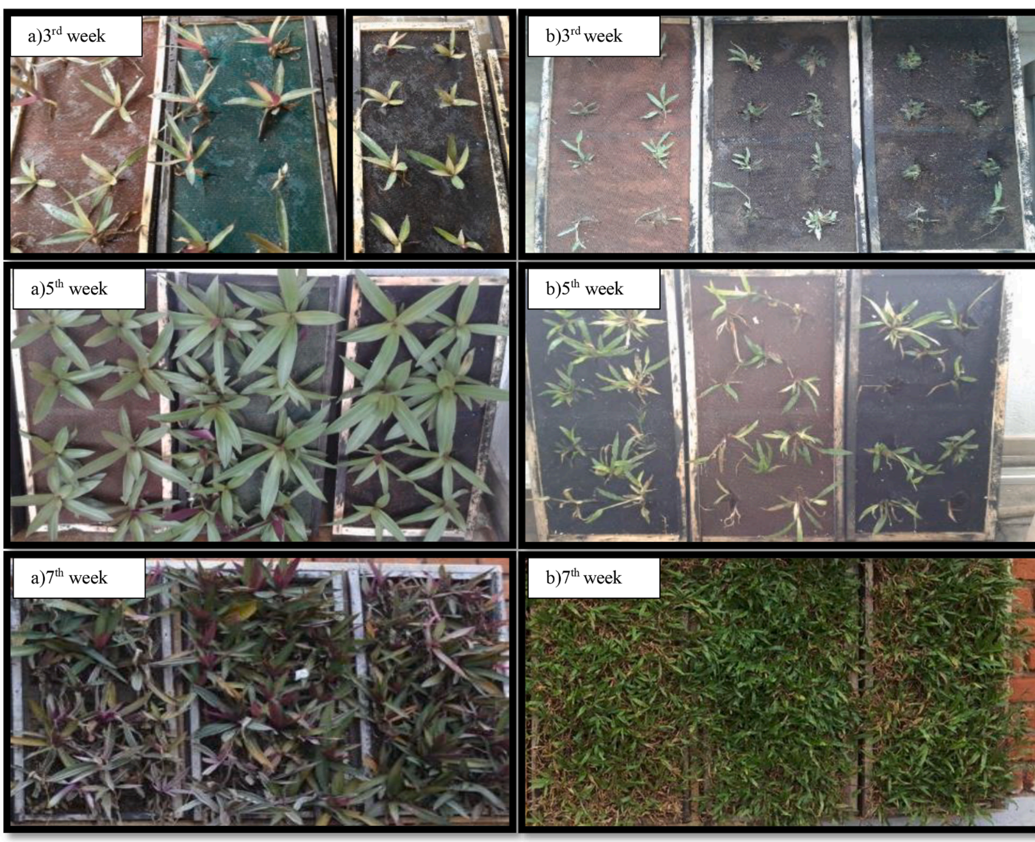

Fig. 6. Growth rate of selected species a) *Rhoeo spathacea* b) *Axonopus fissifoliu.*

living wall with *Axanopus fissifoliu* to the building envelope were simulated. 3D model of the selected government administrative buildings of Colombo, Matara and Kandy cities were created in the software with and without green living walls. Validation of the ENVI-met to test the feasibility of applying *Axanopus fissifoliu* showed a 0.78 of R^2 value for the simulated temperature from the software and actual measured data. It can be realistic to apply in microclimatic simulations with *Axanopus fissifoliu* green living walls since in this simulation model R^2 value was more or less equal to 1.

3.3.1. Site modeling results

Sethsiripaya administrative complex - Colombo existing building model results, average temperature between 26.98 °C and 33.71 °C while the highest temperature value of 33.71 °C at 11.00 h. After enclosing the building with *Axanopus fissifoliu* vertical green living wall, 2.07 °C of maximum temperature reduction has been recorded. With the *Axanopus fissifoliu* green living wall average temperature was varied between 26.96 °C and 31.99 °C where maximum temperature was 31.99 °C at 11.00 h (Fig. 9a).

Existing building model of Matara municipal council showed average temperature between 26.61 °C and 31.91 °C while the highest

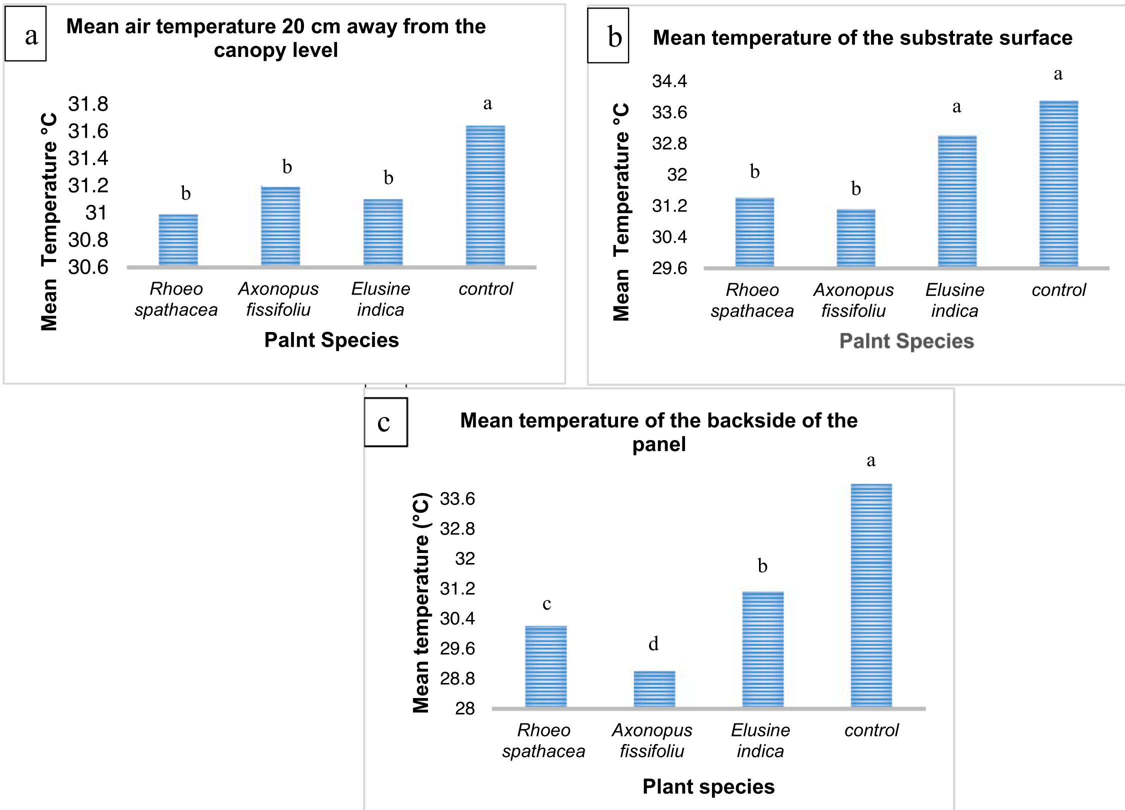

Fig. 7. a) Mean air temperature 20 cm away from the canopy level b) Mean temperature of the substrate surface c) Mean temperature of the backside of the panel (the different letters are significantly differ according to Duncan multiple range test. $P > 0.05$, $n = 5$).

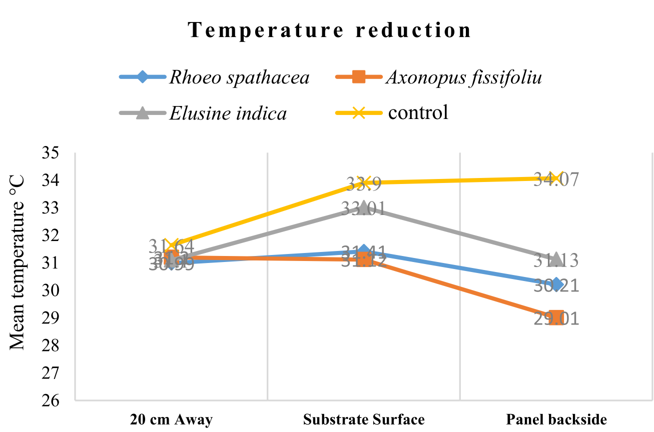

Fig. 8. Temperature reduction of each species behind the panel.

temperature value of 31.91 °C has been recorded at 11.00 h. With the *Axanopus fissifoliu* green living wall, average temperature varied between 26.16 °C and 30.53 °C where maximum temperature value of 30.53 °C has been recorded at 13.00 h (Fig. 9b).

Kandy municipal council building has been constructed mainly with concrete wall material and terracotta roofing material. Temperature of the Kandy municipal building varied between 24.85 °C and 32.37 °C in the existing building condition and varied between 25.04 °C and 30.06 °C in the simulated green living wall condition. Maximum temperature reduction was due to *Axanopus fissifoliu* green living wall and it was 2.03 °C at 12.00 h (Fig. 9c).

Temperature fluctuation in the study sites have been depicted by temperature contour maps developed with LEONARDO visualized tool in ENVI-met (Fig. 10). It showed the clear color comparison between existing conditions of the site with the simulated green living wall conditions.

4. Discussion

4.1. Plant selection study (Phase 01)

Integrating ecosystem and biodiversity values into metropolitan planning and development processes is one of the major sustainable development goals (SDG 15.9) under the sustainable development goals-2030 agenda and pronounced target to mitigate impacts of climate change such as UHI effect (Sustainable Development Goals | UNDP, 2021). Inserting vegetation as vertical green living walls into the urban ecosystems is a crucial factor in this aspect and plant growth and thermal performances are precisely significant to consider. The appropriate vegetation depends on (a) climatic conditions, (b) the building envelope characteristics and (c) the surrounding atmospheric conditions, in which the green living wall is implanted. According to this study the best suitable plant species for vertical green living walls in the tropical region were *Axonopus fissifoliu, Rhoeo spathacea* and *Elusine indica* which have shown better growth and thermal performances.

Among the selected nine plant species, *Dieffenbachia* spp*, Bigonia* spp and *Tectaria* spp formed tall stems that showed a tendency to grow downward and across the vertical green living wall panels. This shortcoming restricted the capability of the plant to successfully grow in the vertical environment (Blanusa et al., 2012). The stems and the leaves were responsible to break with the high growing rate of the shrub. Therefore, it will cause to mechanical damages such as human handling, high wind velocities resulting in green living walls (Perini et al., 2011). Therefore, *Dieffenbachia* spp, *Bigonia* spp and *Tectaria* spp have not been survived in the vertical living environment.

According to the Perkins and Joyce (2012), perennial species which

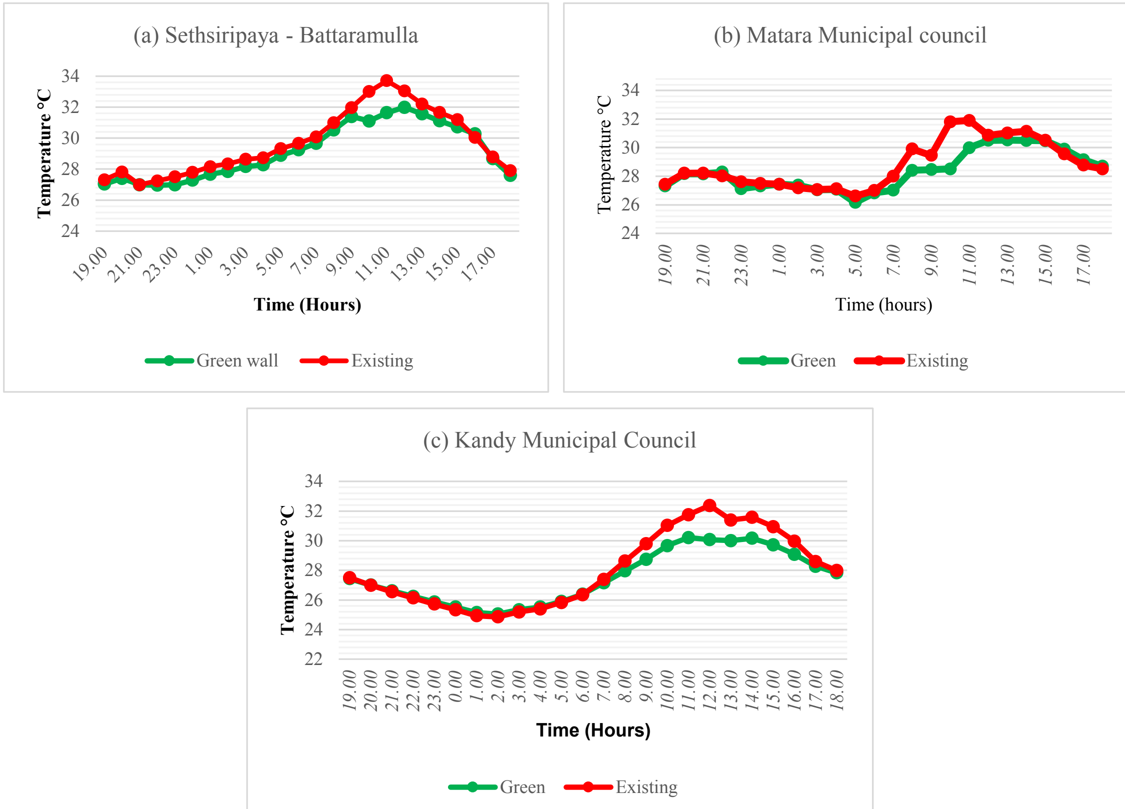

Fig. 9. Temperature variations in each location with the time a) Sethsiripaya b) Matara urban council c) Kandy urban council.

spreaded by forming a mat or with dense clump plants were considered as the best for long-term coverage for extensive green living walls. Therefore, *Axonopus fissifoliu, Elusine indica* and *Rhoeo spathacea* (dense clumping) can be incorporated into the green living walls with the best growing ability to cover the total surface within a short time period, accordingly.

The dense canopy of variegated foliage also make *Rhoeo spathacea* an attractive option for vertical green living walls (Badrulzaman et al., 2015). Thick foliage layers can create an immobile air layer amongst the leaves and diverse foliage layers creates different shading effects. Due to material properties of the verticle module, the moisture retention capacity of the system can also be varied (Wu et al., 2009). Plant leaves perform as solar filters which can absorb solar heat and that absorbed heat can be used for the chemical reactions occurred inside the plants (Weinmaste, 2020). Therefore, growing plants with higher LAI near buildings evade solar heat absoption by building walls hence it will reduce the inside temperature (Larsen et al., 2014; Perini and Ottelé, 2012). During the present research study period LAI of *Rhoeo spathacea, Axonopus fissifoliu* and *Elusine indica* were 3.21, 3.20 and 2.21, respectively. According to Megan Kanaga (2020), the LAI values over 1 is indicated as a total ground coverage by the vegetation. Therefore, *Rhoeo spathacea*, *Axonopus fissifoliu* and *Elusine indica* have the potential to cover optimum surface area and apparently decrease the temperature through the leaf canopy.

Plants such as *Rhoeo spathacea* have wider surfaces and dark green leaves which have a greater surface area with maximum quantity of chlorophyll and therefore they can apprehened elevated amount of carbon dioxide from the atmoshphere (Mohamed et al., 2018). The influence of green living wall over carbon sequestration or carbon sinking, correspondingly makes a substantial approach for UHI effect mitigation (Mohamed et al., 2018). According to a study of Tamási and Dobszay (2016), one tonnes of CO_2 extent can be saved by 22 m^2 plant leaf area. A study conducted in Beijing, China has showed that 3.33 × 1012 kJ of heat absorbed by urban vegetation and it disclosed that 60% of energy usage reduction for air conditioners. Simultaneously carbon emission has been reduced by 243,000 tons of CO_2 per summer season (Mohamed et al., 2018).

According to a study conducted by Manso and Castro (2015), the ideal height range for vertical green living walls were 10 to 15 cm where small plants have a tendency to less wind damage and better maintenance capability (Sunakorn and Yimprayoon, 2011). *Rhoeo spathacea*, *Elusine indica* and *Axonopus fissifoliu* showed ideal plant heights supporting to the findings of Manso and Castro (2015) where the plant height of each species were below 15 cm.

In this study plant species showed less pest and disease damage during the study period. Further, less pest and disease damages will reduce maintenance cost due to less applications of pesticides (Timur and Karaca, 2013). There were no visible signs of water deficit and wilting or leaf abscission during the trial period. This shows that a 60 × 40 × 5 cm wall panel in tropical climate may be satisfactorily maintained with an irrigation system that delivers 1.08 L/m^2 /week.

4.2. Plant thermal performances assessment (Phase 02)

Temperature reduction in each plant species varied during the study period. *Axonopus fissifoliu* showed the highest temperature reduction and *Elusine indica* showed the lowest temperature reduction amongst selected species. *Rhoeo spathacea* also showed a significant amount of temperature reduction (5.06 °C) in this study. Thermal performance of a vertical green living walls were mainly depend on plant coverage and the density (Radić et al., 2019). Increasing the number of layers of the green living wall system (plant density, plant container, supportive structure, substrate, air gap between wall and the panel) would assist in temperature reduction inside the wall. This can be due to the blocking direct solar radiation which can be amplified by increasing the thickness of the wall structure (Perini et al., 2011).

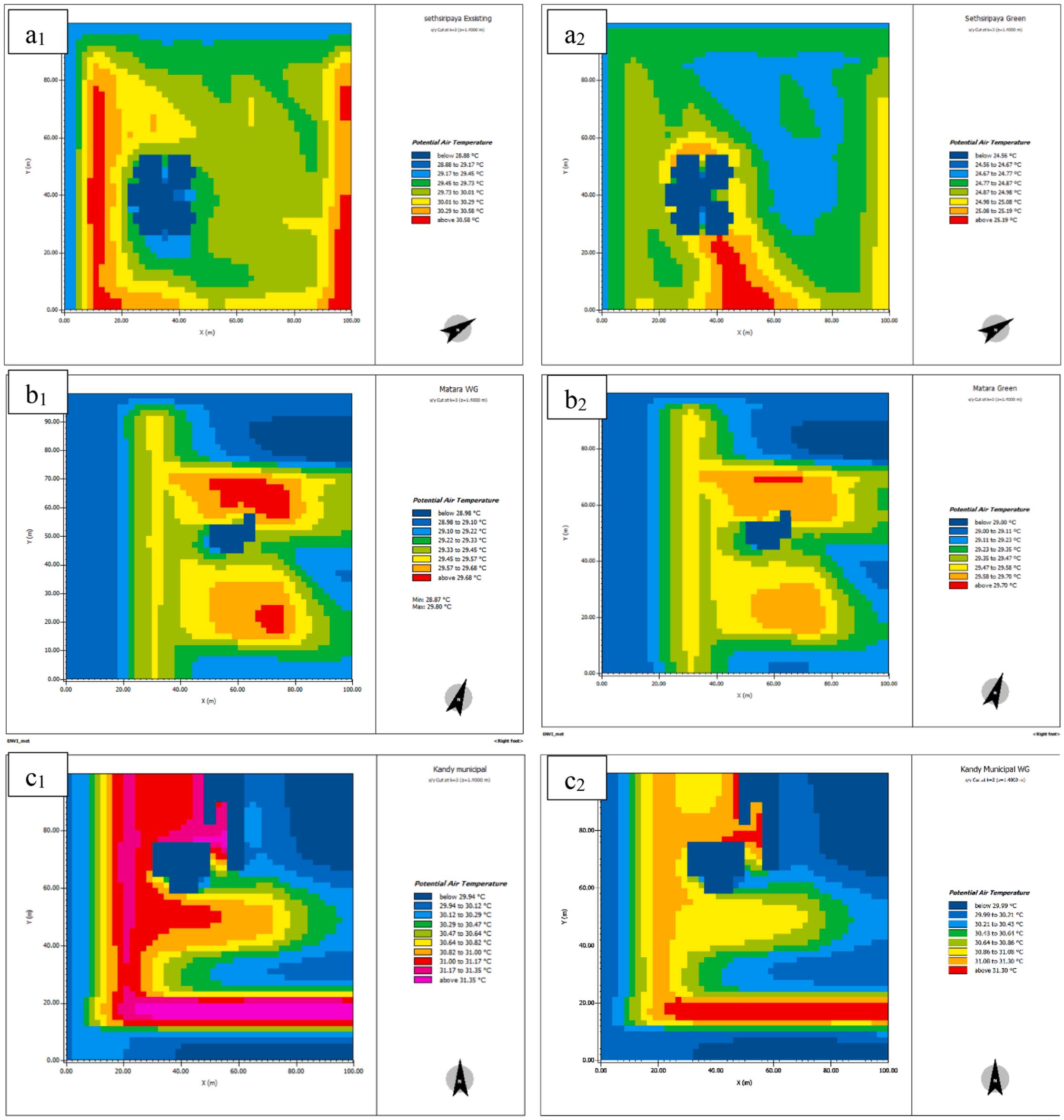

Fig. 10. Temperature profile in selected study sites by LEONARDO a_1) Sethsiripaya administrative complex (Colombo) a_2) Sethsiripaya administrative complex with vertical living wall b_1) Matara Urban council Building b_2) Matara Urban council Building with vertical living wall c_1) Kandy Urban council building c_2) Urban council building with vertical living wall.

Rhoeo spathacea, Axonopus fissifoliu and *Elusine indica* did not show a significant difference in temperature reduction at 20 cm away from the canopy level. According to the Perini et al. (2011), temperature reduction at 1 m distance away from the canopy level in green living wall and green facades were not significant and it was 0.17 °C and 0.13 °C, respectively.

Agreeing to Wong et al. (2010), higher cooling effect can be gained by having a higher foliage density and different vegetation colors. According to Cameron et al. (2014), a maximum temperature reduction of 20.8 °C in exterior wall and 7.7 °C in interior wall have been recorded by a green living wall system in China. The average temperature of the air layer between the wall and the vegetation was 3.1 °C cooler than that of the ambient air.

During the study, the highest temperature reduction was recorded by the plants which have the highest foliage density and the highest LAI. The dense canopy of the *Rhoeo spathacea* and the highest coverage by *Axonopus fissifoliu and Elusine indica* make an attractive choice for green living walls as it helps to reduce temperature of the surrounding environment (Yeh, 2015).

Green living walls have an ability to create an additional cooling effect by using moist growing media and it has a little impact on the microclimate of the wall (Susorova et al., 2013). *Rhoeo spathacea* have shown that a 3.11 °C temperature reduction in internal vertical green living wall surface (Rupasinghe and Halwatura, 2020). Different leaf cover patterns between the species, showed different cooling effects per unit area of leaf (Kosaka et al., 2013). Greater potential for total cooling could be observed as it has thicker canopy, great leaf area and leaf orientation (Cameron, 2014). The size of the leaf blades and the morphology can affect the thermal aspects of the green living walls (John and Unsworth, 2008; Raji et al., 2015).

The rate of convection and conduction of heat from the leaf surface increases as the size of the leaf reduces (Tilley et al., 2014). Therefore, the cooling effect of *Axonopus fissifoliu* was greater than that of *Rhoeo spathacea* though it has smaller leaves. Furthermore, interactions between leaf area, geometry of leaf, color of the leaf and other microclimatic parameters such as solar radiation result differences in the cooling efficiency (Azkorra et al., 2015; Giordano et al., 2015; Önder and Akay, 2014). Proper selection and management of vegetation for vertical green walls can reduce temperature by 10 ◦C which ultimately save 20% energy consumption (Haggag, 2010). According to Safikhani et al. (2014), condition of the plantings and the properties of the substrate reduce the temperature in green living walls better than the green façade.

4.3. Simulation study (Phase 03)

Previous studies have been done for validation in ENVI-met software for tropical climate (Ghaffarianhoseini and Berardi, 2015; Qaid and Ossen, 2015) and subtropical climate (Gusson and Duarte, 2016) and R^2 values were 0.96 and 0.69, respectively. Another study in Changwon, South Korea reported that R^2 was 0.52 for urban context simulation and 0.69 in Toronto for humid continental climate (Song and Park, 2015; Wang, 2016). Herath et al. (2017), showed that 0.78, 0.80 and 0.91 R^2 values for asphalt, cement and grass, respectively in 1.5 m height above ground in Sri Lanka. Therefore, ENVI-met software can be considered as the best suited software for this study.

Selected study sites were situated in the city center and human gathering is conspicuous because those are government administrative centers. Therefore, high CO_2 emission is creating high thermal uncomforting conditions around the buildings (Nuruzzaman, 2015). According to Bousse (2009), emission of air pollutants due to automobile has increased air temperature as particulate matter absorbs solar radiation.

Decorative concrete blocks have been used for pavements and floors in Kandy municipal council building. It may be a cause for high temperature around the building yet there was reasonable vegetation. Cooling effect by evapotranspiration and water infiltration can be obstructed by impermeable surfaces (Sailor, 2006).

Further, Sethsiripaya is a 14-storey building and using high amount of air conditioners. Majority of the building wall consists with glass windows. It caused to block long solar wave and reflects them back to the environment. This resulted in high heat inside the building and extra use of air conditioners (Palomar et al., 2019).

Albedo values of the construction materials of the building, pavements and the roads can trigger high temperature around these buildings. All the building walls were constructed by concrete with terracotta roofing and concrete slabs. Use of asphalt roads, concrete, and bricks which have high albedo values absorb solar radiation and re-emit to the environment which caused to increased temperature (Huttner et al., 2008). According to Takkanon and Chantarangul (2019), non-shaded asphalt surfaces showed a big difference in temperature range of 39.00 °C–49.70 °C. With the green vegetation it had been dropped by 3.80 °C in Bangkok. Few previous studies have been suggested that different materials for surfaces with low albedo values ranging from 0.41 to 0.77 (Levinson and Akbari, 2002; Sailor, 2006).

Multistory buildings create urban canopy by absorbing heat reflected by near buildings causes' urban heat island effect (Masson, 2006; Wu et al., 2018). According to Priyadarsini et al. (2008), tall and densely located buildings affect the wind velocity and then reduced cooling effect. Further, massive use of air conditioners caused increasing temperature in the environment as it absorbing indoor heat and releases it to outside (Okwen et al., 2011).

Around the studied buildings there was less vegetation. Plant absorbs solar energy and CO_2 then release water vapor to the environment during photosynthesis while helps to cool the atmosphere. Therefore, less amount of vegetation may results reducing cooling effect (Akbari et al., 2001). Addition of 10% of vegetation usually reduces temperature by 0.6 K (Theeuwes et al., 2017).

5. Conclusion

According to this study *Roheo spathacea, Elusine indica* and *Axonopus fissifolius* showed the highest rate of survival (100%) and coverage on the vertical green living wall. *Desmodium triflorum, Centella asiatica, Axonopus compressus, Dieffenbachiae spp, Tectaria spp*, and *Bigonia spp* have declining survival rates in the vertical green living walls. Growth rates of *Roheo spathacea, Elusine indica* and *Axonopus fissifolius* were higher than the expected and they achieved full coverage within 8 weeks of transplanting. *Roheo spathacea, Elusine indica* and *Axonopus fissifolius* reached up to ideal plant height (5–15 cm) for the green living walls within 8 weeks of transplanting. When considering the LAI, *Roheo spathacea, Elusine indica,* and *Axonopus fissifolius* showed the highest LAI (>1) and therefore, the cooling effect of the wall was significant. It can be concluded that the maximum temperature of the wall surface can be decreased by covering walls with vegetation. For the green living walls, heat changes up to 5.06 °C were detected. *Axonopus fissifolius* displayed the highest temperature reduction amongst other species. Software calibration has verified that the ENVI-met is realistic to use in tropical climatic simulations in urban contexts with *Axonopus fissifolius* with the results of R^2 of simulated temperature values compared to measured actual ground values in equivalent location. According to the simulation phase possible maximum temperature reduction by using *Axonopus fissifolius* plant in vertical green living walls in tropical climate vary between 2.03 °C and 3.29 °C. Sethsiripaya Administrative complex (Colombo), Matara urban council building and Kandy urban council building showed temperature reductions of 2.07 °C, 3.29 °C and 2.03 °C, respectively. Further studies on a broader range of plant species, substrate preparations and irrigation management is mandatory to assess for long-term usage in green infrastructure for Sri Lanka. It is necessary to determine the sustainability of green living wall plants and media in a tropical context, both with and without supplementary irrigation.

CRediT authorship contribution statement

T.A.N.T. Perera: Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **G.Y. Jayasinghe:** Conceptualization, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - review & editing. **R.U. Halwathura:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Software, Supervision. **H.T. Rupasinghe:** Conceptualization, Investigation, Methodology, Resources, Software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Abad, M., Noguera, P., Puchades, R., Maquieira, A., Noguera, V., 2002. Physico-chemical and chemical properties of some coconut coir dusts for use as a peat substitute for containerized ornamental plants. Bioresour. Technol. 82 (3), 241–245. https://doi.org/10.1016/S0960-8524 (01) 00189-4.

Ahmad, N., Sharma, S., Singh, V.N., Shamsi, S.F., Fatma, A., Mehta, B.R., 2011. Biosynthesis of silver nanoparticles from desmodium triflorum: a novel approach towards weed utilization. Biotechnol. Res. Int. 454090 https://doi.org/10.4061/2011/454090.

Aigbokhan, E.I., 2015. Dieffenbachia sequine (Jacq.) Scott (Araceae) – a potential invasive threat to rainforest ecosystems in Nigeria aceous plant in Nigeria. Nigerian J. Botany 25 (2).

Akbari, H., Pomerantz, M., Taha, H., 2001. Cool surfaces and shade trees to reduce energy use and improve air quality and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy, 70 (3), 295–310.

Alexandri, E., Phil, J., 2008. Temperature decreases in an urban canyon due to living walls and green roofs in diverse climates. Build. Environ. 43 (4), 480–493. https://doi.org/10.1016/j.buildenv.2006.10.055.

Anderson, M., 2016. Embrace the Vertical: Creating Living walls-Available at: http://www.newenglandgrows.org/pdfs/ho_Anderson14HandoutFRI.pdf (Accessed: 18 August 2017).

Arunbabu, V., Sruthy, S., Antony, I., Ramasamy, E.V., 2015. Sustainable greywater management with Axonopus compressus (broadleaf carpet grass) planted in sub surface flow constructed wetlands. J. Water Process Eng. 7, 153–160. https://doi.org/10.1016/j.jwpe.2015.06.004.

Awang, Y., Shaharom, A.S., Mohamad, R.B., Selamat, A., 2009. Chemical and physical characteristics of cocopeat-based media mixtures and their effects on the growth and development of celosia cristata. Am. J. Agric. Biol. Sci. 4 (1), 63–71. https://doi.org/10.3844/AJAB.2009.63.71.

Azkorra, Z., Pérez, G., Coma, J., Cabeza, L.F., Bures, S., Álvaro, J.E., Erkoreka, A., Urrestarazu, M., 2015. Evaluation of living walls as a passive acoustic insulation systems for buildings. Appl. Acoust. Elsevier Ltd 89, 46–56. https://doi.org/10.1016/j.apacoust.2014.09.010.

Badrulzaman, J., Said, I., Md Reba, M.N., Rasidi, M.H., 2015. An experimental study on bioclimatic design of vertical greenery systems in the tropical climate-The Malaysia-Japan Model on Technology Partnership. In: International Proceedings 2013 of Malaysia-Japan Academic Scholar Conference, pp. 369–376. https://doi.org/10.1007/978-4-431-54439-5_37.

Blanusa, T., Monteiro, M.M.V., Fantozzi, F., Vysini, E., Li, Y., Cameron, R.W.F., 2012. Alternatives to Sedum on green roofs: can broad leaf perennial plants offer better "cooling service"? Build. Environ. Elsevier 59, 99–106. https://doi.org/10.1016/j.buildenv.2012.08.011.

Bousse, Y.S., 2009. Mitigating the urban heat island effect with an intensive green roof during summer in Reading. UK with an intensive green roof during summer in Reading, UK.

Briargate Botanicals, 2020. Plant Information. Retrieved May 24, 2020, from http://www.briargate.org/herbs/info/viewHerb.cfm?herbID=1720.

Cameron, R.W.F., Taylor, J.E., Emmett, M.R., 2014. What's 'cool' in the world of green façades? How plant choice influences the cooling properties of green walls. Build. Environ. 73, 198–207. https://doi.org/10.1016/j.buildenv.2013.12.005.

Charoenkit, S., Yiemwattana, S., 2016. Living walls and their contribution to improved thermal comfort and carbon emission reduction: a review. Build. Environ. Elsevier Ltd 105, 82–94. https://doi.org/10.1016/j.buildenv.2016.05.031.

Chen, J., Zhou, C., Li, F., 2020. Quantifying the green view indicator for assessing urban greening quality: an analysis based on Internet-crawling street view data. Ecol. Ind. 113 https://doi.org/10.1016/j.ecolind.2020.106192.

Chen, Q., Li, B., Liu, X., 2013. An experimental evaluation of the living wall system in hot and humid climate. Energy Build. Elsevier B.V. 61, 298–307. https://doi.org/10.1016/j.enbuild.2013.02.030.

Chin, S., Board, N.P., 2014. Research Technical Note RTN Urban Greenery Series, (December 2013). https://doi.org/10.13140/RG.2.1.4506.7924.

Department of Employment Economic Development and Innovation (DEEDI), 2016. Weeds of Australia - Biosecurity Queensland Edition Fact Sheet: Andropogon gayanus. Identic Pty Ltd. Special edition of Environmental Weeds of Australia for Biosecurity Queensland. Queensland. Retrieved from https://keyserver.lucidcentral.org/weeds/data/media/Html/andropogon_gayanus.html.

Flatbud, 2017. Rhoeo Discolor - Flatbud.com. Available at: https://flatbud. Com / plant/ rhoeo-discolor (Accessed: 11 November 2017).

Flora Fauna Web - Plant Detail - Centella asiatica 2013. Retrieved November 22, 2017, from https://florafaunaweb.nparks.gov.sg/Special-Pages/plant-detail.aspx?id=5347.

Galagoda, R.U., Jayasinghe, G.Y., Halwatura, R.U., Rupasinghe, H.T., 2018. The impact of urban green infrastructure as a sustainable approach towards tropical micro-climatic changes and human thermal comfort. Urban For. Urban Greening 34, 1–9. https://doi.org/10.1016/j.ufug.2018.05.008.

Ghaffarianhoseini, A., Berardi, U., 2015. Thermal performance characteristics of unshaded courtyards in hot and humid climates. Build. Environ. 87, 154–168.

Gilman, E.F., 1999. Rhoeo spathacea. Gainesville: Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences. University of Florida.

Giordano, R., Montacchini, E., Tedesco, S., 2015. Indoor Performances of Living Wall Systems: Tools and Requirements', pp. 351–356.

Gusson, C.S., Duarte, D.H.S., 2016. Effects of built density and urban morphology on urban microclimate - calibration of the model ENVI-met V4 for the subtropical Sao Paulo Brazil. Procedia Eng. 169, 2–10. https://doi.org/10.1016/j.proeng.2016.10.001.

Haggag, M.A., 2010. The use of living walls in sustainable urban context: with reference to Dubai, UAE. WIT Trans. Ecol. Environ. 128, 261–270.

Herath, H.M.P.I.K., Halwatura, R.U., Jayasinghe, G.Y., 2017. Evaluation of green infrastructure effects on tropical Sri Lankan urban context as an urban heat island adaptation strategy Urban Forestry and Urban Greening Evaluation of green infrastructure effects on tropical Sri Lankan urban context as an urban heat. Urban For. Urban Green. Elsevier 29 (November), 212–222. https://doi.org/10.1016/j.ufug.2017.11.013.

Huttner, S., Bruse, M., Dostal, P., 2008. Using Environment to simulate the Impact of Global Warming on the Microclimate in Central European Cities. In: 5th Japanese-german Meeting on Urban Climatology. October 2008. pp. 307–312.

Iasiah, A., Khanif, Y., 2004. Physical and chemical properties of coconut coir dust and oil palm empty fruit bunch and the growth of hybrid heat tolerant cauliflower plant. Agric. Sci. Technol. 27 (2), 121–133.

Irga, P.J., Braun, J.T., Douglas, A.N.J., Pettit, T., Fujiwara, S., Burchett, M.D., Torpy, F. R., 2017. The distribution of living walls and green roofs throughout Australia: do policy instruments influence the frequency of projects? Urban For. Urban Greening 24, 164–174. https://doi.org/10.1016/j.ufug.2017.03.026.

Islam Shafrqul, A.K.M., Ismail, Z., Ahmad, M.N., Othman, A.R., Dharmaraj, S., Shakaff, A.Y.M., 2003. Taste Profilins of Centella Asiatica by a -Cste Sensor. Sensors Mater. 15 (4), 1. http://eprints.usm.my/3120/1/Taste_Profiling_Of_Centella_Asiatica_By_A_Taste_Sensor.pdf.

Jagoe, R., 1940. Carpet Grass, Axonopus Spp. in, pp. 109–118. Available at: https://lkcnhm.nus.edu.sg/dna/docs/b094882567dc9f90e372e2ad1312d591.pdf.

Jillian, M., 2016. How smog, soot, greenhouse gases, and other top air pollutants are affecting the planet-and your health. Available at: https://www.nrdc.org/stories/air-pollution-everything-you-need-know (Accessed: 5 November 2017).

John, M., Unsworth, M., 2008. Principles of Environmental Physics. 3rd ed. Edited by Jeanne Lawson. US. Available at: https://booksite.elsevier.com/samplecha pters/97801 25051033/Sample_Chapters/01~Front_Matter.pdf (Accessed: 27 March 2018).

Kosaka, Y., Xayvongsa, L., Vilayphone, A., Chanthavong, H., Takeda, S., Kato, M., 2013. Wild edible herbs in paddy fields and their sale in a mixture in Houaphan Province, the Lao People's Democratic Republic. Econ. Bot. 67 (4), 335–349. https://doi.org/10.1007/s12231-013-9251-6.

Koyama, T., Yoshinaga, M., Hayashi, H., Maeda, K., Yamauchi, A., 2013. Identification of key plant traits contributing to the cooling effects of green façades using freestanding walls. Build. Environ. 66, 96–103. https://doi.org/10.1016/j.buildenv.2013.04.020.

Larsen, S.F., Filippín, C., Lesino, G., 2014. Thermal simulation of a double skin façade with plants. Energy Procedia 57 (December), 1763–1772. https://doi.org/10.1016/j.egypro.2014.10.165.

Levinson, R., Akbari, H., 2002. Effects of composition and exposure on the solar reflectance of Portland cement concrete. Cem. Concr. Res. 32 (11), 1679–1698.

Liu, M., Dai, Y., Li, Y., Luo, Y., Huang, F., Gong, Z., Meng, Q., 2008. Madecassoside Isolated from Centella asiatica Herbs Facilitates Burn Wound Healing in Mice. Planta Med. 74 (08), 809–815. https://doi.org/10.1055/s-2008-1074533.

Liu, W., Zhan, J., Zhao, F., Yan, H., Zhang, F., Wei, X., 2019. Impacts of urbanization-induced land-use changes on ecosystem services: a case study of the Pearl River Delta Metropolitan Region, China. Ecol. Ind. 98, 228–238. https://doi.org/10.1016/j.ecolind.2018.10.054.

Malys, L., Musy, M., Inard, C., 2014. A hydrothermal model to assess the impact of living walls on urban microclimate and building energy consumption. Build. Environ. 73, 187–197. https://doi.org/10.1016/j.buildenv.2013.12.012.

Macera, L.G., Pereira, S.R., De Souza A.L.T., 2017. Survival and growth of tree seedlings as a function of seed size in a gallery forest under restoration. Acta Botanica Brasilica, 31(4), 539–545. Epub September 21, 2017.https://doi.org/10.1590/0102-33062017abb0075.

Manso, M., Castro, Gomes J., 2015. Living wall systems: a review of their characteristics. Renew. Sustain. Energy Rev. 41, 863–871. https://doi.org/10.1016/j.rser.2014.07.203.

Marzluff, J.M., Endlicher, W., Bradley, G., Simon, U., Shulenberger, E., Alberti, M., Ryan, C., Zumbrunnen, C., 2008. Urban ecology: an international perspective on the interaction between humans and nature. Urban Ecol. Int. Perspect. Interact. Humans Nat. (January 2008), pp. 1–807. doi: 10.1007/978-0-387-73412-5.

Masi, F., Bresciani, R., Rizzo, A., Edathoot, A., Patwardhan, N., Panse, D., Langergraber, G., 2016. Living walls for greywater treatment and recycling in dense urban areas: a case-study in Pune. J. Water Sanitation Hygiene Dev. 6 (2), 342–347. https://doi.org/10.2166/washdev.2016.019.

Masson, V., 2006. Urban surface modeling and the meso- scale impact of cities. Theor. Appl. Climatol. 84 (1–3), 35–45.

Maw, M.B., Ding, H.B., Yang, B., Win, P.P., Tan, Y.H., 2020. Taxonomic studies on Begonia (Begoniaceae) in Myanmar I: Three new species and supplementary description of Begonia rheophytica from Northern Myanmar. PhytoKeys 138, 203–217. https://doi.org/10.3897/phytokeys.138.38721.

Mazzali, U., Peron, F., Romagnoni, P., Pulselli, R.M., Bastianoni, S., 2013. Experimental investigation on the energy performance of Living Walls in a temperate climate. Build. Environ. 64, 57–66 doi: 10.1016 /j.buildenv.2013.0 3.005.

Megan Kanaga, C., 2020. Leaf Area Index. Available at: https://wiki.landscapetoolbox.org/doku.php/remote_sensing_methods:leaf-area_index (Accessed: 17 March 2021).

Mohamed, S., Perisamy, E., Hussein, H., Elyna, N., 2018. Vertical Greenery System in urban tropical climate and its carbon sequestration potential : A review. Ecological Indicators, 91(January 2017), 57–70. https://doi.org/10.1016/j.ecolind.2018.03.086.

Morabito, M., Crisci, A., Guerri, G., Messeri, A., Congedo, L., Munafò, M., 2020. Surface urban heat islands in Italian metropolitan cities: tree cover and impervious surface influences. Sci. Total Environ. 751 https://doi.org/10.1016/j.scitotenv.2020.142334.

Nuruzzaman, M., 2015. Urban heat Island: causes, effects and mitigation measures - a review. Int. J. Environ. Monitor. Anal. 3 (2), 67. https://doi.org/10.11648/j.ijema.20150302.15.

Okwen, R., Pu, R., Cunningham, J., 2011. Remote sensing of temperature variations around major power plants as point sources of heat. Int. J. Remote Sens. 32 (13), 3791–3805.

Önder, S., Akay, A., 2014. The Roles of plants on mitigating the urban heat islands' negative effects. Int. J. Agric. Econ. Dev. 2 (22), 18–32.

Ortiz, O.O., Croat, T.B., 2017. A new species of Dieffenbachia (Araceae) from Limón Province, Costa Rica. Webbia 72 (2), 149–153. https://doi.org/10.1080/00837792.2017.1330008.

Palomar, T., Silva, M., Vilarigues, M., 2019. Impact of solar radiation and environmental temperature on Art Nouveau glass windows. Herit. Sci. 7, 82. https://doi.org/10.1186/s40494-019-0325-3.

Pan, B.T.C., Kao, J.J., 2021. Comparison of indices for evaluating building green values based on greenhouse gas emission reductions. Ecol. Ind. 122 https://doi.org/10.1016/j.ecolind.2020.107228.

Patil, S.M., Kachhiyapatel, R.N., Rajput, K.S., 2019. Review on the genus Tectaria cav. from India. Plant Sci. Today 6 (2), 170–182. https://doi.org/10.14719/pst.2019.6.2.511.

Percy, M., 2000. Plant Fact Sheet - Orchardgrass. USDA NRCS National Plant Data Center, Louisiana. Retrieved from https://plants.usda.gov/factsheet/pdf/fs_axfi.pdf.

Pérez, G., Coma, J., Sol, S., Cabeza, L.F., 2017. Green facade for energy savings in buildings: the influence of leaf area index and facade orientation on the shadow effect. Appl. EnergyElsevier Ltd 187, 424–437. https://doi.org/10.1016/j.apenergy.2016.11.055.

Perera, T.A.N.T., Nayanajith, T.M.D., Jayasinghe, G.Y., Premasiri, H.D.S., 2021. Identification of thermal hotspots through heat index determination and urban heat island mitigation using ENVImet numerical micro climate model. Modeling Earth Syst. Environ. 1–18 https://doi.org/10.1007/s40808-021-01091-x.

Perini, K., Ottelé, M., Fraaij, A.L.A., Haas, E.M., Raiteri, R., 2011. Vertical greening systems and the effect on air flow and temperature on the building envelope. Build. Environ. Elsevier Ltd 46 (11), 2287–2294. https://doi.org/10.1016/j.buildenv.2011.05.009.

Perini, K., Rosasco, P., 2013. Cost–benefit analysis for green façades and living wall systems. Build. Environ., 70, 110–121. doi: 10.1016/j.buIldenv. 2013.08.012.

Perini, K., Ottelé, M., 2012. Vertical greening systems: contribution to thermal behavior on the building envelope and environmental sustainability. Eco-Architect. 165 (4), 239–249. https://doi.org/10.2495/ARC120221.

Perkins, M., Joyce, D., 2012. Living Wall and Green Roof Plants for Australia. RIRDC-Available at. https://rirdc.infoservices.com.au/items/11-175.

Phutthai, T.P., Hughes, M., Ridith, K.S., 2012. S0960428612000078 287.292. Edinburgh Journal of botany 69 (2), 287–292. https://doi.org/10.1017/S0960428612000078.

Phutthai, T.P., Sridith, K., 2010. Begonia pteridiformis (Begoniaceae), a new species from Thailand. Retrieved from Thai Forest Bulletin (BOTANY) 38, 37–41. https://www.researchgate.net/publication/268432504_Begonia_pteridiformis_Begoniaceae_a_new_species_from_Thailand.

Priyadarsini, R., Hien, W.N., David, C.K.W., 2008. Microclimatic modeling of the urban thermal environment of Singapore to mitigate urban heat island. Sol. Energy 82 (8), 727–745.

Qaid, A., Ossen, R., 2015. Effect of asymmetrical street aspect ratios on microclimates in hot: humid regions. Int. J. Biometeorol. 59, 657–677.

Radić, M., Dodig, M.B., Auer, T., 2019. Green facades and living walls-a review establishing the classification of construction types and mapping the benefits. Sustainability (Switzerland) 11 (17), 1–23. https://doi.org/10.3390/su11174579.

Rahman, M., Rahman, M., Hassan, A., 2012. Seed germination of two medicinal plants: Bangladesh. J. Plant Taxon 19 (2), 209–212.

Raji, B., Tenpierik, M.J., van den Dobbelsteen, A., 2015. The impact of greening systems on building energy performance: a literature review. Renewable Sustainable Energy Rev. Elsevier Ltd 45, 610–623. https://doi.org/10.1016/j.rser.2015.02.011.

Ranker, T.A., Haufler, C.H., 2008. Biology and evolution of ferns and lycophytes. Cambridge University Press. Available at: https://books.google.com/books?id=js9JnwEACAAJ (Accessed: 5 December 2017).

Rizwan, A.M., Dennis, L.Y.C., Liu, C., 2008. A review on the generation, determination and mitigation of Urban Heat Island. J. Environ. Sci. 20 (1), 120–128. https://doi.org/10.1016/S1001-0742(08)60019-4.

Roehrs, R., Gilman, E.F., 1999. Dieffenbachia maculata 'Rudolf Roehrs' 1. Gainesville: Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences. University of Florida.

Rupasinghe, H.T., Halwatura, R.U., 2020. Benefits of implementing vertical greening in tropical climates. Urban For. Urban Greening 53. https://doi.org/10.1016/j.ufug.2020.126708.

Safikhani, T., Abdullah, A.M., Ossen, D.R., Baharvand, M., 2014. Thermal Impacts of Vertical Greenery Systems', pp. 5–11. doi: 10.1515/rtuect-2014-0007.

Sailor, D.J., 2006. Mitigation of urban heat islands-recent progress and future prospects. Paper presented at the Paper presented on American meteorological society 6th symposium on the urban environment and forum on managing our physical and natural resources.

Sharma, A., Conry, P., Fernando, H.J.S., Hamlet, A.F., Hellmann, J.J., Chen, F., 2016. Green and cool roofs to mitigate urban heat island effects in the Chicago metropolitan area-evaluation with a regional climate model Green and cool roofs to mitigate urban heat island effects in the Chicago metropolitan are. Environ. Res. Lett. 11 (6), 1–16. https://doi.org/10.1088/1748-9326/11/6/064004.

Sheweka, S.M., Mohamed, N.M., 2012. Green facades as a new sustainable approach towards climate change. Energy Procedia 18, 507–520. https://doi.org/10.1016/j.egypro.2012.05.062.

Dong, Shi-Yong, Chen, Cheng-Wei, Tan, Shi-Shi, Zhao, Hui-Guo, Zuo, Zheng-Yu, Chao, Yi-Shan, Chang, Yi-Han, 2017. New insights on the phylogeny of Tectaria (Tectariaceae), with special reference to Polydictyum as a distinct lineage: New insights on the phylogeny of Tectaria. J. Systemat. Evol. 9999 (9999), 1–9. https://doi.org/10.1111/jse.12292.

Shouliang, C., Phillips, S.M., 2006. Axonopus p. Beauvois, Ess. Agrostogr, Flora of China 22, 530–531.

Simon, B.K., Sharp, D., 2002. CD Ausgrass: grasses of Australia. Australian Biological Resources Study, Canberra and Environmental protection Agency, Brisbane.

Singh, M.C., Singh, K., Singh, J., 2018. Indirect method for measurement of leaf area and leaf area index of soilless cucumber crop. Adv. Plants Agric. Res. 8 (2), 188–191. https://doi.org/10.15406/apar.2018.08.00311.

Singh, S.G., Parmar, N., Patel, B.R., 2015. A review on Shalparni (Desmodium gangeticum DC) and Desmodium species (Disodium triflorum DC. and Desmodium laxiflorum DC.) – Ethnomedicinal perspectives. J. Med. Plants Stud. 3 (4), 38–43.

Smith, T.M., Smith, R.L., 2015. Elements of Ecology. Elements of Ecology. Pearson Education.

Song, B., Park, K., 2015. Contribution of greening and high-albedo coatings to improvements in the thermal environment in complex urban areas. Adv. Meteorol. 2015 https://doi.org/10.1155/2015/792172.

Steed, S., Marble, C., Boyd, N.S., Macrae, A., Fnu, K., 2016. Biology and Management of Goosegrass (Eleusine indica (L.) Gaertn.). Ornamental Plant Production. Gainesville: Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences. University of Florida.

Sunakorn, P., Yimprayoon, C., 2011. Thermal performance of biofacade with natural ventilation in the tropical climate. Procedia Eng. 21, 34–41. https://doi.org/10.1016/j.proeng.2011.11.1984.

Susorova, I., Angulo, M., Bahrami, P., Stephens, B., 2013. A model of vegetated exterior facades for evaluation of wall thermal performance. Build. Environ. 67, 1–13. https://doi.org/10.1016/j.buildenv.2013.04.027.

Sustainable Development Goals | UNDP, 2021. Available at: https://www.undp.org/content/undp/en/home/sustainable-development-goals.html (Accessed: 17 March 2021).

Takkanon, P., Chantarangul, P., 2019. Effects of urban geometry and green area on thermal condition of urban street canyons in Bangkok. Architect. Sci. Rev. Taylor and Francis Ltd. 62 (1), 35–46. https://doi.org/10.1080/00038628.2018.1534724.

Tamási, A., Dobszay, G., 2016. Requirements for designing living wall systems – analysing system studies on Hungarian projects. Periodica Polytechnica Architect. 46 (2), 78–87. https://doi.org/10.3311/ppar.8337.

Theeuwes, N.E., Steeneveld, Gert-Jan, Ronda, R.J., Holtslag, A.A.M., 2017. A diagnostic equation for the daily maximum urban heat island effect for cities in northwestern Europe. Int. J. Climatol. 32 (1), 443–454.

Tilley, D., Alexander, A., Chang, A., Price, C., Welch, A., Brian Tjaden, Scott, W., 2014. Green Facades: Ecologically Designed Vertical Vegetation Helps Create a Cleaner Environment. Available at: https://extension.umd.edu/sites/ extension.umd. Edu/files/_docs/publications/FS-978 Green Facades- Ecological Designed Vertical Vegetation.pdf (Accessed: 16 October 2020).

Timur, Ö.B., Karaca, E., 2013. Advances in Landscape Architecture', in Vertical Gardens. Çankırı 587–622. https://doi.org/10.5772/55763.

Tsoka, S., Tsikaloudaki, A., Theodosiou, T., 2018. Analyzing the ENVI-met microclimate model's performance and assessing cool materials and urban vegetation applications–a review. Sustainable Cities Soc. Elsevier Ltd 55–76. https://doi.org/10.1016/j.scs.2018.08.009.

Ulpiani, G., 2020. On the linkage between urban heat island and urban pollution island: three-decade literature review towards a conceptual framework. Sci. Total Environ. 751 https://doi.org/10.1016/j.scitotenv.2020.141727.

Wang, Y., 2016. The effect of urban green infrastructure on local microclimate and human thermal comfort. British J. Psychiatry. https://doi.org/10.1192/bjp.111.479.1009-a.

Weerakkody, U., Dover, J.W., Mitchell, P., Reiling, K., 2017. Particulate matter pollution capture by leaves of seventeen living wall species with special reference to rail-traffic at a metropolitan station. Urban For. Urban Greening. Elsevier GmbH 27, 173–186. https://doi.org/10.1016/j.ufug.2017.07.005.

Weinmaste, M., 2020. Are living walls as "green" as they look? An Introduction to the Various Technologies and Ecological Benefits of Living walls. J. Green Build. 4 (4).

Wong, C.C., Sharudin, M.A.M., Rahim, H., 1985. Shade tolerance potential of some tropical forages for integration with plantations. Legumes, MARDI Res. Bull, 13(3), pp. 249–269. Available at: http://ejtafs.mardi.gov.my/jtafs/13-3/Shade tolerance.pdf (Accessed: 18 November 2017).

Wong, N.H., Kwang Tan, A.Y., Chen, Y., Sekar, K., Tan, P.Y., Chan, D., Chiang, K., Wong, N.C., 2010. Thermal evaluation of vertical greenery systems for building walls. Build. Environ. Elsevier Ltd 45 (3), 663–672. https://doi.org/10.1016/j.buildenv.2009.08.005.

Wu, C., Niu, Z., Tang, Q., Huang, W., Rivard, B., Feng, J., 2009. Remote estimation of gross primary production in wheat using chlorophyll-related vegetation indices. Agric. For. Meteorol. 149 (6–7), 1015–1021. https://doi.org/10.1016/j.agrformet.2008.12.007.

Wu, D., Wang, Y., Fan, C., Xia, B., 2018. Thermal environment effects and interactions of reservoirs and forests as urban blue-green infrastructures. Ecol. Ind. 91 (February), 657–663. https://doi.org/10.1016/j.ecolind.2018.04.054.

Xu, C., Haase, D., Pribadi, D.O., Pauleit, S., 2018. Spatial variation of green space equity and its relation with urban dynamics: a case study in the region of Munich. Ecol. Ind. 93, 512–523. https://doi.org/10.1016/j.ecolind.2018.05.024.

Yeh, Y.P., 2015. Living wall- The Creative Solution in Response to the Urban Heat Island Effect. Available at: http://www.nodai.ac. jp/cip/ iss/ english /9th _ iss / fullpaper/3-1-4nchu-yupengyeh.pdf (Accessed: 4 October 2017).