INTEGRATION OF DOUBLE SKIN GREEN WALL AS A SUSTAINABLE DESIGN APPROACH IN TROPICAL CONTEXT

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DECLARATION

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ABSTRACT

Global warming and energy crisis are two of the biggest issues the world faces today which require immediate mitigatory actions. Building sector plays a major role in contributing to these issues due to the high energy consumption and carbon emissions. Highly dense urbanities directly contribute in urban heat island effect thus local warming. Therefore, researchers have given considerable interest on the building envelop design with the concerns for energy efficiency, aesthetic appearance and sustainability. As a result, integration of green facades with buildings has rapidly evolved due to the aesthetic appeal and sustainable benefits such as uplifting the urban environmental conditions by promoting air quality, reducing heat island effect and etc. However, adaptation of vertical greenery is still at an initial stage in Sri Lanka.

The research was initiated to introduce vertical greenery to a broader context and to develop an innovative modular green wall system for building facades as a sustainable building envelop in Sri Lankan context. Field studies were conducted in identifying the potential of introducing a vertical greening system and benefits of existing vertical greening systems in tropical Sri Lankan context. Modular panel and green wall system development was conducted as on-site experiments and the thermal performance evaluation and long-term benefits of the proposed modular panel vertical greening system was conducted as on-site investigations combined with software simulations.

Results of the field investigations on the perception on vertical greening in local context demonstrated that general public, building occupants and the building designers are willing to accept the vertical greening as a sustainable approach for buildings. Yet, lack of knowledge on the vertical greening systems, maintenance methods and their benefits and misconceptions on related costs have impeded the popularization of vertical greening. Identified existing vertical greening types in local context; living walls, indirect and direct green facades are beneficial in reducing the surface temperature of buildings where living walls recorded the highest temperature reduction of 10.15^{o}C. Internal air temperature reduction was recorded to be 2.21^{o}C, 1.82^{o}C and 0.66^{o}C by living wall, indirect green façade and direct green façade.

Pilot and extended field investigations on plant selection for the proposed vertical greening system resulted in shortlisting two species, from which *Axonopus compressus* was selected as the best plant species where a maximum 10.08^{o}C external wall surface temperature reduction and 3.15^{o}C internal surface temperature reduction was recorded. The experimental studies on finalizing growth media resulted 1:1/2:1/2: 1/4 coir: sand: compost: soil ratio as the growth media with the best compaction and the permeability for the plant growth in the proposed vertical greening system. Proposed system is advantageous as it can be easily introduced to existing structures and as the panels can be handled separately allowing easy installation and easy replacement with minimum technical support. Size of the modular panel was finalized as 600mm (width) x 900mm (height) for easy handling and the fiber was selected as the material due to strength and durability.

Developed walling system recorded a surface temperature reduction of 17.26^{o}C, 7.89^{o}C in external wall and internal wall surface and a temperature reduction of 2.89^{o}C of internal air temperature. Simulation studies conducted in building scale and urban scale resulted significant indoor air temperature reduction, cooling load reduction and urban air temperature reduction when integrating the proposed modular panel green wall whereas the quantifiable long-term benefits are achievable in terms of savings from energy consumption and façade maintenance and numerous un-quantifiable benefits related to sustainability and health.

Keywords: *Green facades, Living walls, Building envelop, Double skin, Sustainable buildings*

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1. INTRODUCTION

1.1 General

Rapid globalization and growth of population in today's world, urbanization trends have attracted higher number of people to urban contexts triggering high population densities and space scarceness in urbanities. This rapid acceleration of population and urbanization magnify the demand for more living spaces leading to higher artificially constructed structures and relatively less greenery. As a result, more buildings are being constructed in urban areas replacing the greenery which triggers a grave danger for the environment. According to United Nations (UN) population statistics, by 2010 half of the global population has been recorded to be living in urbanities. The records signify an increase of urban population from 729 million to 3.5 billion within the time period of 1950 - 2010. By 2018 this has increased up to 4.2 billion (UN,2019).

As UN predicts, continuation of this trend would lead urban population to be two third of the world population by year 2045 (UN,2014). Due to the prompt economic growth, urbanization in Asia too has accelerated while increasing the need for more buildings and infrastructure development. Consequently, urban heat islands are created causing extreme climatic conditions and elevating air temperature increasing the demand for comfortable indoor environments thus craving for more energy.

Human induced activities which trigger the current global issues such as global warming, environmental impacts, health related issues, thermal discomfort as well as higher cooling energy demand have become widely discussed topic in world calling attention for sustainable buildings which negates the higher energy consumption and its adverse effects. Energy efficiency in building sector is highly important as it is responsible for more than one fifth of energy consumption worldwide annually. Operational energy of the building represents a higher percentage of energy consumption of a building throughout the building life cycle which is directly impact on the occupant comfort. Therefore, energy efficiency of buildings is identified as a main factor when considering the building related emissions, fossil fuel depletion and climate change phenomena.

Having these considerations in mind over the years, researchers have focused on the envelop design of buildings concerning energy efficiency, aesthetic appeal and sustainability. Building façade is a key element of the building envelop which separates the building interior and exterior. It has a higher potential to act as a climatic filter which take only the favorable impacts from the outside.

In this context, use of double skin envelop is a sound design option to improve climate response and then improve energy efficiency of a building. A typical external double skin envelop can consists of three layers i.e. fourth skin outside, third skin inside and the cavity or buffer space in between. The double skin envelop allows greater control over natural ventilation and solar radiation through the use of multiple skins as climatic buffer zones. Therefore, double skin envelop interventions are recognized as better options to act as climatic filters to maintain comfortable indoor environments.

On the other hand, where sustainability of buildings is highly discussed, based on the identified benefits in improving building thermal performance as well as in improving urban environments, vertical greening has gained attention of researches and designers. Improving air quality and reducing heat island effect, promoting bio diversity and etc. which promotes the wellbeing of people are such identified benefits of vertical greening. Further, vertical greenery enables restoration of lost greenery due to man-made structures. Increasing number of buildings and urban density urge the need to promote vertical greenery in cities.

Unawareness and the lack of technology has led to less use of vertical greening. Moreover, vertical greenery can help in recreating the link between nature and human. Having identified the benefits of double skin envelop and vertical greening it is understood that amalgamation of these two strategies can be highly beneficial in achieving the aimed sustainable goal in buildings. Moreover, development of a green wall panel system to be installed as a double skin envelop intervention has never been practiced in Sri Lankan context.

The research is aimed at finding the potential of the concept of integrating green wall panels as a double skin envelop to make the buildings more sustainable. Demand optimization of buildings’ operational energy is discussed as a priority in making buildings more climate responsive thus energy sustainable than fixing engineered systems in the first place. Design interventions at a hierarchical order are discussed while envelop contribution to this effort is brought forward as a major concern for this study. The research contributes to establish that building design: specifically, the building facade can play a key role in addressing indoor overheating involving a shift towards new bioclimatic design solutions focusing on passive climate control with External Double Skin Envelops (EDSE). Objective of this is to improve the building to a envelop dependent status. With field studies, on-site investigations and simulations the idea will be researched. The proposed modular panel green wall system will be a sustainable solution as a double skin intervention that adopt novel green concepts while promoting indoor comfort as well as improving outdoor environment. Modular panel system will allow for easy replacement and maintenance of the external green skin.

1.2 Need of the study

Building envelop becomes the major component which interacts with the outdoor environment thus has the potential to address the above requirements. Greening cities and buildings are rapidly developing in the field of architecture and building construction, due to the visual appeal and sustainability related benefits they offer. However, climate response of buildings located in the tropics is problematic due to complexity associated with heat gain potential through the building envelop as a whole.

Further, heat generation inside a building is a contributor to the problem of indoor overheating. Thus, in order to become energy efficient which is the base of being truly green, buildings need to have climate responsive characteristics. Even though many researches have been conducted internationally on vertical greening applications, it is less researched in tropical Sri Lankan context. Therefore, the benefits of using green wall as sustainable building envelop in local context is still not yet fully identified. Since there is a greater potential in implementing a sustainable green wall system to address the sustainable building design requirements, the research is aimed at developing a green wall system as a double skin facade in Sri Lankan context.

In Sri Lanka, implementation of vertical greening is still at an initial stage and the knowledge on vertical greening systems is very limited. No proper study has been conducted to identify vertical greening types, characteristics and the reasons for implementing vertical greening in existing situation. Therefore, first step of the research aimed at investigating the existing Vertical Greening Systems (VGS) of Sri Lankan context, plant selection, watering systems and maintenance details related to existing vertical greening. Despite the interest of many professionals in utilizing green facades in buildings, the hard data on the effect and performance of using these green facades are either missing or not well investigated.

Utilizing green wall as a double skin is less researched in tropical contexts. Thus, the potential of using green wall as an external double skin is still not fully identified. The research investigates the potential to develop a modular green panel considering the performance characteristics, potential of usage, most appropriate size of the module, fixing angle, maintenance and etc. to be used as a double skin as a sustainable building design intervention in the tropical context.

Further, the research explores the benefits achievable by integrating developed vertical greening system in actual situation, its contribution on the building facade performances and the environmental and economic aspects. Identifying the gap in existing vertical greening situation where the true potentials are less concerned, it is questioned how the design of building envelop and in particular a double skin façade integrated with vertical greening help to mitigate this problem of overheating and contribute to create passive cooling inside a building during a typical warm day. It is further questioned to what extend this can be achieved and what performance characteristics can be identified and formulated.

The work is focused mainly on to the thermal performance behavior of double skin facade integrated with vertical greening the tropics. The study is limited to climatic and building context in Colombo as it represents the warm humid climate and building typologies in the country. Selecting buildings for on-site performance evaluation has limitations. The study is carried out on selected buildings with vertical greenery representing the typologies identified in vertical greening classification.

1.3 Objectives

As a developing country facing the energy crisis and health issues due to human impacts on environment, many public and private institutions are now heading towards finding novel methods to address the sustainable development requirement. There is more attention now in attempting to implement sustainable design frameworks in building designs. The outcome of this research will highly contribute to innovate sustainable building facade system thus addressing the less practiced building design interventions for sustainable development by mitigating heat island effect, reducing indoor heat gain and improving the air quality.

With the need for the study, the research is aimed at focusing on the energy sustainability of buildings in the tropics and how this can be achieved through innovative building design; specifically, with the building facade design. However, the significance of building envelop is presented as a constituent of the whole scenario of climate response and how integration of vertical greening can be an ideal solution to overcome these issues. More specific aims and objective may be identified as follows;

1. Identifying the potentials of vertical greening in overcoming the current global issues related to climate change, energy sustainability of buildings and scarcity of greenery in urban contexts.
2. Investigating the current trends, concepts and practices of vertical greening in Sri Lankan context.
3. Developing a green panel module and the wall system to be established as a sustainable external green skin in tropical context investigating the plant type, growth medium, growing system, module size, weight and fixing methods, water drainage methods, maintenance etc.
4. Monitoring the performance characteristics such as thermal behavior, durability and etc. of the module to develop as a sustainable building façade.
5. Evaluating the benefits of vertical greening integrated as double skin green wall in building context and in micro & macro urban contexts and the long-term cost benefit analysis of the proposed vertical living wall system.

1.4 Methodology

The methodology of the work is designed to find solutions for the research problems. Therefore, the method is mainly grounded on a theoretical basis with the support of literature.

More focus is given to the achievable passive cooling effect of the vertical greening when integrated to the building facade. Characteristics and performance evidence of vertical greening in various building applications and different climatic situations are shown in order to justify the potential of utilizing vertical greening as a double skin facade for climate responsiveness and energy sustainability of the built environments. The research methodology involves developing a modular panel vertical greening system. The method focuses on investigating the most appropriate plant type, growth medium and etc. for an external green wall that is durable and work best in tropical context.

Methodology and research plan involved

1. A literature survey was carried out to identify the background of vertical greening systems and their applications in international context.

2. A field investigation was carried out to identify buildings integrated with vertical greening in local context and to assess and evaluate the thermal and environmental performance of identified cases.

   Stage 01: A photographic survey was conducted in Colombo city limits to identify well established existing VGS and existing VGS types were verified. From the observed twenty case studies, nine cases (three cases representing each VGS type) were further investigated for in depth analysis.

   Stage 02: Three cases were further investigated to identify the thermal benefits of existing VGS types to building interior.

3. Three separate questionnaire surveys were conducted to identify the perception on vertical greening of occupants of VGS integrated buildings, designers and general public on the trends and concepts of vertical greening.

4. A field Study was conducted to investigate the plant species most suitable for the proposed VGS in terms of survival & thermal behavior.

Prototype modular panels with twelve shortlisted plant species were developed, maintained and monitored to select the best suited plant. Detailed investigation on the selected plant species were carried out to further identify its growth requirements.

5. Laboratory tests were conducted to identify the best growth media mix for the vertical green wall.

6. The modular panel was developed to achieve the most suitable size, weight with easy fixing methods and maintenance with a system of watering the panel and drainage while identifying the best angle to fix the panel for the growth of the plant.

6.Thermal performance of the individual modular green wall panels were conducted.

7. The modular panel vertical green wall was developed to be integrated as the external skin of a double skin facade.

8. Field studies were conducted to identify the irrigation system and irrigation sequence and also the thermal performance of the VGS.

9.Simulation studies were conducted to evaluate the thermal and environmental performance of the vertical greening to building interior in terms of energy efficiency and temperature moderation.

10. Simulation studies were conducted to assess the benefit of vertical greening in macro and micro urban contexts in terms of urban temperature modification.

11. Long term cost benefit analysis of the proposed vertical greening system was conducted to identify the environmental, energy and economic benefits.

1.5 Main findings

The thesis is based on development of modular panel vertical green wall as an external skin of a double skin facade in tropical climatic condition that is economic, durable and thermally effective.

Questionnaire surveys on the perception on vertical greening integration in local context demonstrated that general public, building occupants as well the building designers are willing to accept the vertical greening as a sustainable approach for buildings. However due to the less knowledge on the VGS, benefits, maintenance methods, the concept of vertical greening has not been fully adapted to the local context. Further, the fear of high costs in terms of installation and maintenance has caused doubts in integrating vertical greening.

The existing vertical greening types in local context were identified as living walls, direct green walls and indirect green walls. From the three types indirect green walls were much popular due to the easy installation and maintenance. All three vertical greening types signified to be beneficial in thermal regulation. However, in terms of thermal benefit of the three types, Living Wall Systems (LWS) were identified to be more beneficial which recorded a maximum temperature reduction of 10.15^{o}C at the façade shaded by the living wall and a reduction of 2.21^{o}C in internal air temperature. When considering the average Relative Humidity (RH) and Carbon dioxide (CO_2) profiles, increment of RH by 1.6% - 1.8% and an average CO_2 reduction by 0.63% were recorded at vertical greening systems compared to bare wall control in local tropical climatic condition.

From the twelve-plant species investigated through field investigation of plant selection for the proposed vertical greening system, five plant species namely *Rhoeo spathacea, Axonopus compressus, Portulaca grandiflora, Ophiopogon japonicas and Elusine indica* were shortlisted. Basic thermal performance and survival analysis of the five species resulted in selecting the two species *Rhoeo spathacea* and *Axonopus compressus* as the best two plant species for the proposed VGS. In-depth field analysis two species resulted in finalising *Axonopus compressus* as the plant species for the proposed modular panel vertical greening system which recorded a maximum 10.08^{o}C external wall surface temperature reduction and 3.15^oC internal surface temperature reduction.

Based on the field observations and literature, the growth media was decided to be a mix of coir, sand, compost and soil where coir was selected to be the main component. Laboratory test to obtain the compaction curve and the permeability of the media resulted in finalizing the growth media mix to be 1:1/2:1/2: 1/4 coir: sand: compost: soil ratio which displayed the best compaction and the permeability for the plant growth in the proposed vertical greening system.

Size of the modular panel for the walling system was finalized as 600mm (width) x 900mm (height) which enables easy handling and the material was selected as fiber due to strength and durability. The size and the materiel selection allowed easy installation and minimum technical support while allowing easy replacement of panels when required. Through permeant wilting point and field capacity tests the irrigation sequence and the water requirement for the panels were identified. When installed as an external skin to the building facade, the walling system recorded a temperature reduction of 17.26^oC, 7.89$^oC$and 2.89^oC in external wall surface, internal wall surface and the internal air temperature respectively.

Simulation studies conducted in building scale and urban scale resulted significant indoor air temperature reduction, cooling load reduction and urban air temperature reduction when integrating the proposed modular panel green wall. The quantifiable long-term benefits in terms of savings from energy consumption and façade maintenance and numerous un-quantifiable benefits related to sustainability and health are achievable. Therefore, the proposed vertical system is beneficial both building scale to reduce the energy consumption and occupant comfort as well as in urban context to mitigate Urban Heat Island (UHI) and global warming while promoting sustainable and healthy urban environments.

1.6 Arrangement of the thesis

The chapter breakdown of the thesis is as follows;

Chapter 01 gives an overview of the research with a detailed introduction to the research including aims and objectives, methodology and findings.

Chapter 02 presents the detailed literature review conducted to identify the background of vertical greening, its applications, benefits.

Chapter 03 elaborates the findings of the questionnaire surveys conducted to identify the perception of general public, building occupants and the building designers on vertical greening in local context.

Chapter 04 presents the results of the field studies conducted to identify the existing situation of vertical greening in local context, existing vertical greening types and their thermal benefits.

Chapter 05 is focused on the plant selection and the growth media composition for the proposed living wall.

Chapter 06 presents the development of the individual modular panel and the proposed modular panel vertical greening system as an external skin of a double skin wall.

Chapter 07 presents the results of the simulation studies conducted in building scale and urban scale in evaluating the benefits of the proposed modular panel green wall system applications. Further the long-term cost effectiveness of the proposed VGS application too is presented.

Final chapter presents the conclusions of the study followed by the recommendations for VGS application in local context and directions for further studies in the study area.

2. LITERATURE REVIEW

2.1 Introduction to the chapter

In the present global context, the human population is rapidly increasing, and the energy demand is going up in an unprecedented magnitude. The resultant issues and environmental pollution are enormous where human activities and their effects on mother earth has become a scenario to be discussed in depth. The impacts of human behavior on the environment and their influence on the drastic changes in global climate have reflected on the lives of the humans. Among numerous interventions that are introduced to mitigate such impacts, vertical greening is becoming a trend in urban contexts. This chapter focus on establishing a base to the requirement of introducing the concept of vertical greening to local context. Current global environmental issues are discussed in the chapter signifying how sustainable building interventions specially building envelop design are beneficial in addressing them. Further, potentials of vertical greening applications to mitigate urban environmental issues are discussed with an in-depth analysis on the available literature on vertical greening. Finally, the possibility of combining building envelop design strategies and vertical greening applications in developing an external double skin envelop is discussed.

2.2 Global environmental crisis

Since the mid-19th century, emission of Greenhouse Gases (GHG) rapidly increased leading to the current global issue of global warming. On the other hand, as an inevitable consequence of this global warming phenomena the resultant climate change has increased the severity and the intensity of natural disasters increasing the scale of damages caused by them (Halwatura & Jayasinghe, 2007, 2008; Isobe, 2013). The world is now facing the degree of the threat, necessitating to take every possible mitigatory step to avoid the consequences.

2.2.1 Global warming: the primary environmental issue

Today, among the most discussed topics around the world, global warming is one highly concerned topic which has gained attention in almost all the field areas. It is widely known that the extensive GHG emission due to unprecedented energy use is the primary cause for global warming. Since 1800 AD this GHG emission has risen from 275ppm to 370ppm (Boden et al., 2016). This emission growth during last 200 years is overwhelming as it is threatening to the perfect balance of earth's natural systems which were in equilibrium for millions of years. Lean & Smyth (2009) highlights that a significant correlation between carbon emission, energy use and economic growth based on statistical findings. CO_2 is the main component of greenhouse gases. As Hinkel et al., (2013) records annual rate of CO_2 concentration which had been recorded as 1.4ppm per year during 1960-2005 has risen to 1.9ppm per year during the period of 1995-2005. As the predictions highlight, with the continuation of the current trends CO_2 concentration would increase up to 1000ppm by year 2100 (Bastidas-Arteaga et al., 2013).

This scenario in global climate, specifically greenhouse effect due to the concentration of GHG emitted has caused numerous global issues; including sea level rise and destroying habitats and threatening the existence of many species. Warming of the climate system is unequivocal, as is now evident from various observations on average air and ocean temperature increment, widespread melting of snow and ice and global average sea level rise (Hirashi et al., 2013). According to the report of Intergovernmental Panel on Climate Change (IPCC) impacts of global warming cannot be overlooked as the consequences are faced by each and every living being on earth. Impacts of these trends and planetary risks have been identified in multi-faceted aspects such as impact on basic needs; food, water, health and shelter, impacts on vulnerable populations, regional impacts and etc. (IPCC, 2007). Thus, the area has gained the attention of researchers around the world and the evidence has scientifically proven the rise of global temperature (Macilwain,2000). As per Nordell (2003), during 20th century this increment has been recorded in between 0.4^0C-0.8^0C.

According to the statistics and future projections of IPCC it is said that the world may head towards a global warming of 4^oC. This is predicted to cause numerous long-term trends and planetary risks such as sea level rise, temperature stabilization and CO_2 stabilization which would make a drastic impact and severe threat on eco-systems and habitats. Sea level rise is estimated to be 18-59cm by the end of 21st century due to this global warming phenomena. Adger et al., (2003) highlights unless mitigatory steps are taken immediately the current changes in climate experienced by today will remain for centuries causing more unpredictable conditions. Hinkel et al. (2013) notes that with this phenomenon taking place, it would cause a loss of land approx. 6000-17000km^2 in Japan necessitating 1.6-5.3 million people to migrate. Further IPCC highlights due to the high sea water evaporation the energy levels in cyclones too gets increased causing severe destruction (Pachauri et al., 2015). On the other hand, research evidence emphasizes that due to chlorine ingress and carbonization, the failure life of structures would reduce by 30% whereas the service life by 15 years (Bastidas-Arteaga et al., 2013).

2.2.2 Urbanization and population growth

Beginning of the 20th century recorded a global population of 1.6 billion where it had risen to 6.1 billion by 21st century (Population Reference Bureau [PRB], 2007). Consequently in 2016 it was recorded as 7.4 billion with an average population of 526 per square meter of arable land. The count varies from 239 per square meter in developed countries to 697 per square meter in less developed countries (PRB,2015). With the trend the world population is predicted to be 9.8 billion by 2050.

While the global population growth rate continues to rise, the resultant urbanization too is rising at a rapid pace. As Henderson (2002) states, urbanization is a natural part of development and population growth and urbanization are interconnected. Half of the global population live in urban settlements in present and by the next thirty years total of the world population is predicted to be concentrated in urbanized contexts leading to resource scarcity and challenging the sustainability (Cohen,2006).

2.3 Urban environmental issues

Li et al., (2013) states that the effect of urbanization on variation of temperature in urban contexts is determined by the population size and density, socio economic activities, extent of built environment as well as the anthropogenic activities. Urban areas consist darker artificialized surfaces with low albedo which absorb more incident solar radiation thus, consequently become extremely hot. Then these surfaces gradually release the heat causing rise of air temperature in the surrounding (Kaloustian & Diab, 2015). This aggravates health issues influenced by thermal stress (Tan et al., 2010).

Tam et al., (2015) further explains that heat exchange of incoming and outgoing radiation is altered by urban areas leading to an increment of local temperature. Research conducted in United States of America (USA), Japan, European and Asian countries have signified when annual average temperature rises by 1^{o}C, 2% of heating requirements are reduced where cooling requirements are equally increased (Scott et al., 1994).

2.3.1 Urban Heat Island effect

From the man-made environmental issues global warming is the most threatening issue in present which has number of repercussions. Rapid urbanization is one major contributor to this phenomenon which causes UHI effect that leads to temperature rise in urban centers (Golden,2004; Tam et al., 2015). Unplanned urbanization and haphazard development influence UHI due to dense built mass, high fuel consumption, increased impervious surfaces and declined vegetation creating more heat radiation which then is re-reflected in canyon of buildings. UHI occurs in two folds; canopy layer heat island and boundary layer heat island (Weng et al., 2004). Depending on physiographical features in local context and climatic aspects UHI effect varies in different urban contexts (Tam et al., 2015). UHI at night time is found to be maximum under clear and calm nights (Oke,1982). The magnitude of urbanization's impact on surface temperature is estimated as 0.06-0.15^{o}C respectively based on population data and satellite data of night-light (Kalnay & Cai, 2003). A research conducted based on eight Asian mega cities declared a proportionate relationship between daytime UHI and population size (Tran et al.,2006).

2.3.2 Air pollution

Before industrial revolution domestic sources and small-scale industries were the contributors that caused air pollution in a lower scale which gradually rose with population growth. Yet with the boom of industrialization industries developed in a rapid pace while energy consumption increased in an unprecedented magnitude which led to rapid air pollution increment (Mage et al.,1996). High energy consumption in transport related activities (Poumanyavong et al., 2012) and in buildings are the main contributors for air pollution in urban contexts. Concentration of particle matter and

GHG in urban areas due to pollutant emissions and as byproducts of energy consumption has risen in an increasing pace resulting air pollution in urban areas (Han et al.,2014). This indirectly has caused numerous health diseases. For instance, lead (Pb) mixed fuel burn emission lead to malfunction of liver and kidney as well as reduction of mental development in children and infants (World Health Organization [WHO],2000). As the WHO explains, air pollution has a close link to climate change as the same drivers that influence climate change which also contribute to air pollution as well. Due to population increase, traffic congestion, rapid industrialization and higher energy consumption, the tendency for air pollution increase too magnifies. With the current trend of development, it can be predicted that with the emergence of megacities these air pollution drivers too are to be increased which is a greater challenge to be addressed.

2.3.3 Green depletion

Vegetation is the best natural resource that can positively contribute to mitigate the global environmental issues. Trees acts as natural sinks of pollutants as well as GHG and cool the surrounding through evapotranspiration. De Fries et al., (2010) highlights increment of consumption level due to urbanization and international and urban-based demands for agricultural products have heavily influenced on deforestation. Urbanization calls for change of land use mainly for construction activities, infrastructure development and etc. which deprive productive land and green cover leading to climate change (Kalnay & Cai, 2003). In this context urban green spaces are much valued in terms of mitigating the present environmental issues. Jim & Chen (2003) states urban green spaces act as semi-natural areas where significant amount of vegetation is present. Byomkesh et al., (2012) defines urban green spaces as areas in built environments that are covered with man-made or natural vegetation whereas Chiesura (2004) defines urban green spaces as a sustainability measurement in urban areas. Public green spaces, vertical landscaping and rooftop gardens are the three main types of urban green spaces (Wong et al., 2010 a). These spaces comprise of open parks, roadside greenery, courtyards, golf courses, cemeteries, forested woodlots and etc. (Wickramasinghe et al., 2016).

Yet current urbanization trends along with population growth, increasing built mass and unplanned infrastructure development have caused for green depletion in urban areas around the world. Development policies focused on economic development with less concern for environment heavily affect green cover depletion. As Kong & Nakagoshi (2006) highlights the greater Dhaka is one such example where high landscape fragmentation and ecological deterioration took place primarily due to urban-rural migration and lack of proper policy, law and political motivation etc.

Local situation of green depletion

Urbanization trends in Sri Lankan situation has no exception from the global situation. As per the statistics of Department of Census and Statistics, by 2001 the Colombo municipal council works as the country's prime urban center which accommodate 800,637 residential population. Further 400,000 floating population enter and exit the city daily making the total population over one million (Dayaratne,2010). The World Bank report of year 2015 signifies Sri Lanka is experiencing a faster urban expansion in relation to urban population. Subasinghe et al., (2016) highlights sprawl development, continuous decline of greenery, expansion of built spaces, ribbon development, transport corridor expansion as the characteristics of urban foot print of Sri Lanka. By 1998 10km radius in Colombo had been almost urbanized. From 1981-1994 increment of urban areas has increased by 68% and the annual increment has been recorded as 5% (Majeed,1998). In livability index-2017 Sri Lanka has been ranked at 124th place out of 140 cities by the Economist Intelligence Unit (EIU,2017). This indicates Sri Lanka has a critical need of a sustainable framework to actively manage the challenges of rapid urbanization to protect the natural asset and to provide resilience to climate change.

As shown in Figure 2.1 green depletion in Sri Lanka has become a significant issue specially in the Colombo metropolitan. As Li & Pussella (2017) brings out green space decline from 31.0km^2 to 5.02km^2 within the time period of 1980- 2015. This records greenery in local context to be 7.16m^2 per capita value, which is lower than the standard of 8m^2 as per WHO recommendation.

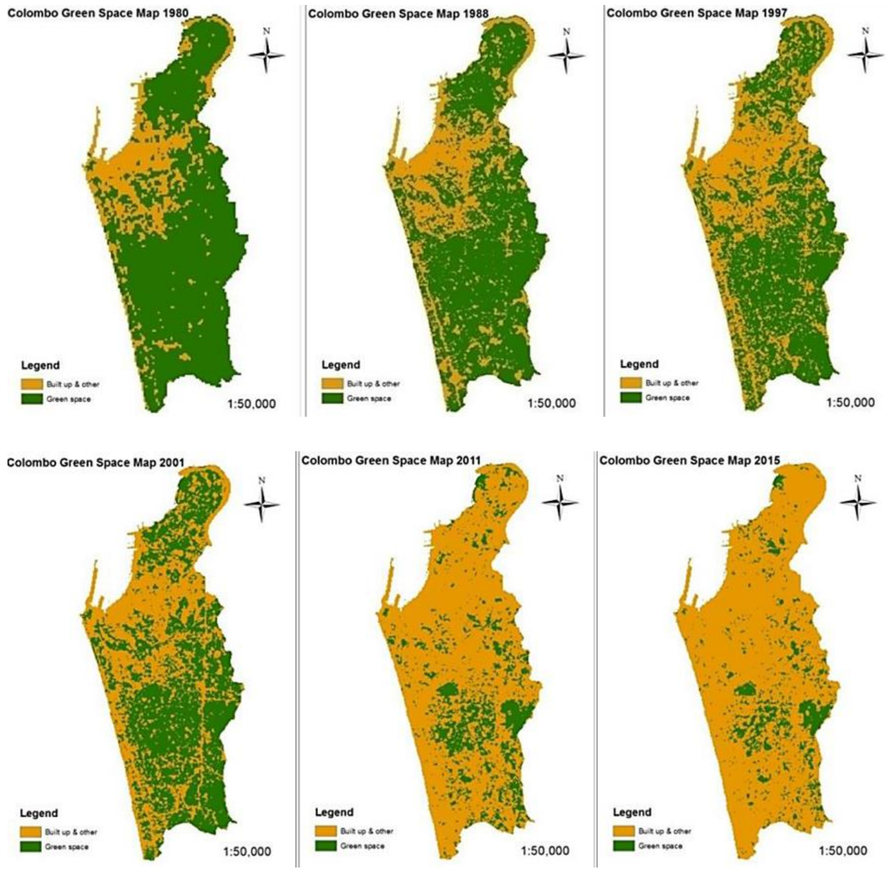


Figure 2.1: Urban green depletion in Colombo urban context from 2001-2015

Source: Li & Pussella, 2017

This reduction is significant since 2001, where the annual reduction has increased up to 0.71km^2 by 2011-2015. The dramatic change of green space due to economic and infrastructure development is significant where most of the green and unoccupied spaces have been drastically transferred to built spaces due to urbanization trends. From 1956 – 2010 green cover depletion is recorded to be from 35.67% to 22.23%. Infrastructure development and expansion of built up spaces are the primary contributing factors for Colombo's rapid green depletion. In 2010 highest green cover was recorded as 49.65% from Narahenpita. Only 30% green cover has been recorded from Kirullapone, Thimbirigasyaya and Cinnamon Gardens from the total land extent (Wickramasinghe *et al.*, 2016). Less than 10% of green cover has been recorded in many areas such as Grandpas North, Kochchikade North and South, Panchikawatte, New Bazar, Fort, Masangasweediya, Gintupitiya, Athulkade East and Maligawatte (Wickramasinghe et al., 2016).

2.4 Energy in the context of global environmental crisis

For about half billion-years life has existed on earth where energy utilization has come across a clear and constant evolution throughout the time (Price,1995). The energy use has risen in an unprecedented magnitude with the social, economic and technical advancement of mankind. Utilization of extrasomatic energy to modify the environment in accordance with various human needs has taken place continuously. While basic human needs expanded, the energy use too has increased in a greater pace (Daly & Cobb, 1994; Keeler & Burke, 2009). This has come to a point where living with no energy is totally impossible. For numerous day-to-day activities energy from renewable and non-renewable resources are being consumed. This trend is critical due to its contribution towards depletion of non-renewable energy and global climate issues. From one side fossil fuels are being depleted much faster whereas world population grows exponentially. In local Sri Lankan context also, energy used is produced mainly from fossil fuels, which is on the increasing side, producing high levels of greenhouse gas emissions (Wijayatunge et al., 2003).

2.4.1 Buildings in the context of energy and environment

The data published by United States Environmental Protection Agency (USEPA) highlights that in regions like USA and Canada people spend 90% of the time inside buildings (USEPA,2008). This helps in giving a clear idea of human dependency on buildings. The scenario is similar in other regions as well. High comfort demands of people cause buildings to be highly energy craving. On the other hand, the technological advancements in the building industry have made significant development making drastic and severe impacts on nature. Buildings are direct and indirect contributors for long term environmental impacts on building microclimate and immediate surrounding (Hunukumbura, 1999). Therefore, a positive relationship between building and its microclimate and surrounding is much important.

Buildings' contribution on global warming and fossil fuel depletion has become evident. Buildings utilize 48% of the fossil fuels and in return emit 40% of the total global CO_2 emission. Throughout the life cycle; from construction to demolition, buildings' contribution for environmental degradation is visible. From pre-building stage for raw material extraction, transport of materials etc. buildings demand energy until the post-building stage to demolish the building when its lifetime ends where demolished building's materials are recycled or reused. Operation stage energy is used for operational and maintenance activities. This energy requirement is inevitable. A building demands for a continuous supply of energy during its operation for cooling/heating, lighting and equipment operation and maintenance. This energy cannot be recovered (Hyde, 2000). Hence it is important to conserve energy as much as possible. Further, the amount of energy consumed in buildings are sensitive to changes in the surrounding climate. Research evidence state 20% change in RH can influence the total energy use of buildings by 2.1%. In general, electricity requirement in cities tend to increase by 2% - 4% for increase of each $1^{o}C$ of temperature (Perez-Lombard et al., 2008).

2.4.2 Energy use for building operation and maintenance

Largest amount of energy consumption of buildings take place in the operational stage which is around 70% - 90% (Adalberth, 2000). Thus, the design of the building offers a high potential of energy saving by reducing the energy need for building operation activities. By today, many international commitments and obligations have stated emission reduction targets which is also related to building energy use and environmental impacts. As Drake (2000) suggests energy efficiency of building operation needs reducing total energy use of the building without any alteration to the conventional energy production approaches. The aim must be to use reasonable amount of conventional resources and maintain lowest demand of conventional energy (Abel, 1994;169). From the evidence it is highlighted that a significant energy saving can be achieved if proper energy efficient strategies are utilized for major building renovations or for new buildings (Hyde et al., 2009).

2.4.3 Improving energy efficiency of buildings

Numerous research results have quantified the temperature rise and global warming impacts projecting warmer days in many parts of the world (Garnaut,2008). As per the findings by Guan (2009) a linear relationship between total energy consumption specifically cooling loads and external air temperature can be established. Results of related simulation studies implies the existing buildings designed to the present climatic condition would face indoor overheating as the air conditioning capacities would not be sufficient to provide the required cooling when the urban temperatures rise due to warming of cities. Therefore, making buildings sustainable and energy efficient to the best possible measures is a vital need in present context specially in warm climate. IPCC reports that buildings; especially non- domestic buildings have a greater potential in becoming cost-effective and mitigating GHG, if architectural and technological initiatives are integrated. Main four areas related to such technical and engineering improvements for buildings are identified as reduction of energy for heating and cooling loads, improving environmental performance of the architectural design inclusive of building envelop, increasing the efficiency of appliances, Heating, Ventilation and Air Conditioning (HVAC) and mechanical systems and increasing the lighting efficiency. Further, behavior of the occupant, culture, choice of consumer, technology use primarily determine the energy use in buildings and CO_2 emission as well (IPCC, 2007). The four staged method that investigates the interplay of different parameters for environmental efficiency of existing non-domestic buildings by Hyde et. al., (2009) focuses on the bioclimatic design interventions. The four stages are;

- Climate analysis and climate change effects on buildings
- Thermal performance investigations and trend analysis of energy consumption of existing buildings or selected buildings
- Integrating design interventions with the building embracing architectural, engineering and behavioral parameters
- Modelling efficiency and effectiveness of the interventions

2.4.4 Energy efficiency of buildings through passive strategies

Among many building related researches, energy sustainability and related area are a key concern due to the current global environmental issues. Building related interventions to reduce energy consumption throughout the building lifecycle; manufacturing of materials, construction of the building, building operation, maintenance and demolition are highly required. According to Hyde (2000) passive strategies of buildings are identified in related to microclimate of the building, form, envelop of the building and efficient systems used.

To achieve energy sustainability of a building climate responsiveness is a vital factor. In terms of building design climate become the major determinant of building form, as the design of the building should be able to moderate the relationship between the climate, building and the occupants. Based on how the building design has responded to the prevailing climate of the context, the thermal landscape and the indoor climate will be influenced. Building envelop has the potential to moderate and filter the impact of outdoor climate to building interiors in terms of air temperature, building operative temperature, airflow and humidity. Occupants always consider comfortability of internal spaces specially in terms of thermal comfort. Thus, when the building design alters indoor climate in an unfavorable way, a significant energy use will take place to address the cooling or heating requirements to create comfortable indoor environments. Therefore, the building design itself should address the requirement of reducing energy use by the utilized passive design interventions.

2.4.5 Buildings in the tropical context

In tropical context which is defined by the warm and humid climate, passive cooling techniques are required to be integrated to building designs to overcome the indoor overheating situations (Figure 2.2). Indoor thermal profile of buildings in tropical contexts is determined by the internal loads and external loads.

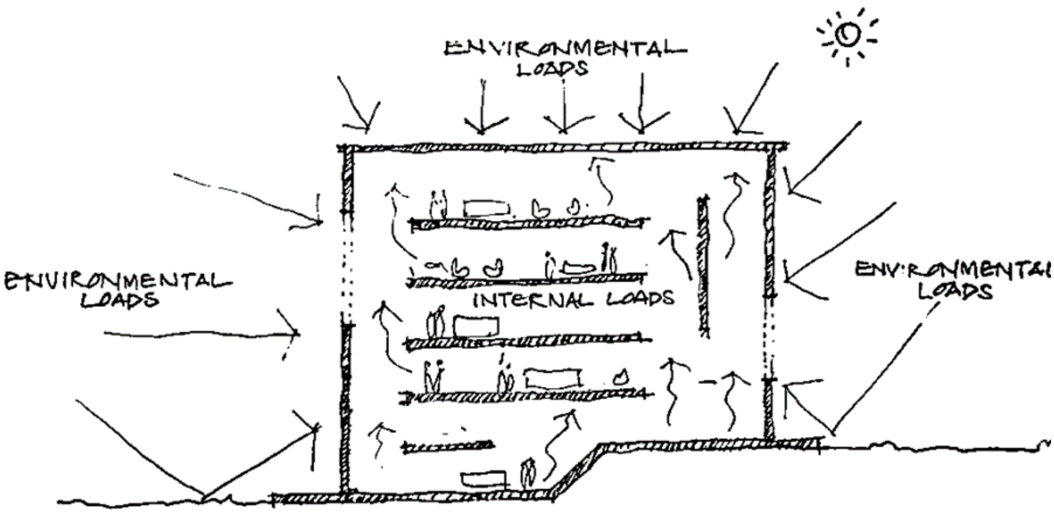


Figure 2.2: Internal loads & external loads of buildings

As Rajapaksha (2013) states environmental loads or externalities such as climate, building design and internal loads or internalities such as occupancy profile, systems and equipment are crucial contributors in determining indoor thermal environment of the building. Based on the intensity the effect can be either environmental load dominant or internal load dominant. In tropical climates environmental dominancy is a common scenario. Tropical warm humid climates prevail in regions extending 15^0 North and South of the equator. Sri Lanka too belongs to tropical climate and does not has a seasonal temperature variation. During a typical year the mean monthly &temperatures vary from 27°C in November to 30°C in April whereas relative humidity may vary in between 70% to 80%. The daily maximum temperatures are high as 29-33°C and the daily pattern in the dry season (September-November and March-May) has diurnal temperature ranges of 7-8°C.

From the perspective of occupant comfort and building design, climatic character of warm humid climate is defined as "the combination of higher temperature and humidity that reduce the surplus heat dissipation of human body" (Rajapaksha, 2014). Further, the bio-climatic charts by Szokolay and Givoni signifies increased air movement evoke indoor comfort in hot humid climates. In tropical context taking preventive methods to avoid indoor overheating is a valuable pre-condition for passive cooling integration for buildings. As Rajapaksha (2014) states, in tropical Sri Lankan context high mass envelop coupled with night ventilation has the ability to reinstate indoor thermal comfort during the warmest period of the year: February, March, April and May.

2.5 Building envelop design for energy efficiency

The material content of the external and internal fabric used in building design is defined as the building envelop. Based on the characteristic of the materials and the three-dimensional profile the thermal behavior of a specific building envelop is determined. Research evidence suggest controlling of all types of radiation is directly influenced by the shading on the building envelops in warm humid climates. Building envelop mass moderate the heat transfer in between interior and exterior of building. As Balaras (1996) states this physical process depends on the building envelop properties. It is further noted that the main aim of building envelop design in warm humid climates should be to limit the thermal gains caused by solar radiation incident and high outdoor air temperatures.

2.5.1 Building envelop: the third skin

Human skin, the first skin that protect the internal body from outside has a biological capacity which enables the heat balance control between outside and human body. Clothing is the second skin that contribute for human comfort based on the region. The building envelop plays the role as a third skin of protection for humans intermediating between building interiors and the outside climatic condition. From the components of building envelop, façade becomes the main component that distinct the interior of the building from the exterior (Ibrahim et al., 2010). Therefore, building façade has the greatest potential to filter the outside climate to take in only the favorable impacts. When taking the nature for inspiration interesting observation can be made on adaptations of animals and plants related to different climatic conditions (Tombazis, 1996). This implies that the design of building envelop should respond to its surrounding climatic condition which signifies building envelop design has to obtain regional characteristics.

2.5.2 External double skin envelops for better thermal regulation

For many decades architects, engineers and researchers have focused on the building envelop design and properties related to sustainability and energy efficiency. The idea of developing the buildings' outer physical wall as a climatic filter has experimented with the beginning of many external wall technologies. This has enabled the distinction of environmental control and optimizing the function of the outside wall layer from load bearing (Fitch, 1972; Diprose & Robertson, 1996). Moreover, number of double skin envelop based practices and research has been conducted using different material combinations (Diprose & Roberson, 1996). Gratia & De Herde (2004a) highlights the possible benefit of double skin envelops in terms of climate responsiveness and energy efficiency. If properly designed, implementing double skin envelop enables soft transition between exterior and interior. Thus, advanced or intelligent building envelops and effective insulation design are required to be applied effectively to the buildings**.**

A typical external double skin envelop can consists of three layers i.e. fourth skin outside, third skin inside and the cavity or buffer space in between. Conduction and convection influenced heat transfer is determined on behavior and velocity of air flow, the air temperature distribution within the cavity or the buffer space, ventilation type and pressure levels inside the EDSE. Studies by Haase (2009) and Wong et al., (2008) provide simulation evidence, based on actual building investigations, for close links between natural ventilation patterns and the function of external double skin envelops. Evidence shows that significant energy savings is possible even for multi-story and high-rise buildings if natural ventilation could be explored through EDSEs. Haase (2009) have attempted to identify main characteristics of double skin envelops in a holistic matrix depending in the air flow behavior which indirectly maintains a dialogue with its associated heat component as well (Figure 2.3).

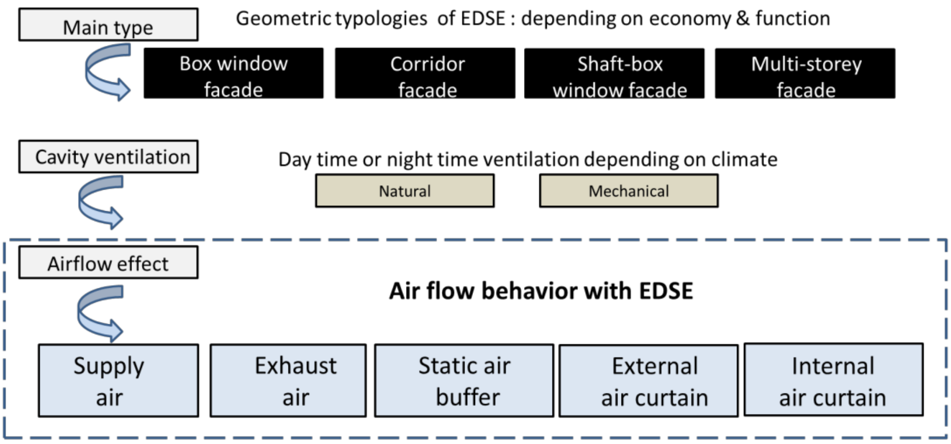


Figure 2.3: Characterization of external double skin envelops

Source: Haase et al., 2009

Double skin envelop has proven to be a better solution as a of climatic filter to create comfortable indoors in tropical climate based on the potential energy saving and indoor air temperature reduction (Rajapaksha et al, 2015). Further, recent researches carried out in the context of Colombo has proved a significant reduction of indoor air temperature due to double skin envelops in buildings (Rajapaksha et al., 2015; Rupasinghe, 2016).

2.5.3 Green wall as the external skin of double skin envelop

In the context of sustainability vertical greening has gained attention around the world as a sustainable application that have multiple benefits in terms of thermal regulation in building interiors and urban greening. As discussed earlier rapid urbanization and increased building population has caused decline of urban greenery. Therefore, conversion of vertical surfaces into vertical greenery offer the potential of increasing much needed urban greenery in densely built urban contexts (Anderson, 2016). Since the availability of vertical surfaces are much higher than that of horizontal surfaces present in urban spaces VGS offer higher possibility to promote greenery in urbanities. With all this the enthusiasm towards VGS implementation is expanding (Fernández et al., 2015).

Vertical greening improves the urban environmental conditions by promoting air quality, reducing heat island effect and etc. thus promoting the wellbeing of occupants. Further, vertical greening offers the opportunity to reestablish the lost greenery replaced by man-made constructions while recreating the link of man and nature. Among the diverse benefits of vertical greening air quality improvement, regeneration of biodiversity and mitigation of heat island effect become prior considerations. However, vertical greening systems are not fully recognized yet, for the environmental benefits and energy-saving opportunities in the buildings, due to inadequacy of data to quantify and evaluate the real sustainability of these (Perini & Ottele, 2014).

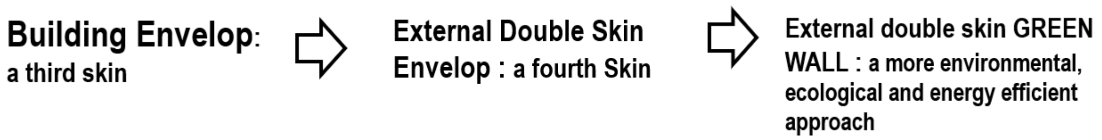


Figure 2.4: Benefit of integrating VGS as a double skin envelop

When compared with the benefits of the double skin envelop, it can be assumed that the integrating green wall as the external leaf of the double skin is undoubtedly much more beneficial (Figure 2.4). The air gap between the vertical green wall would play the role of the cavity in between the two layers of the double skin envelop which will act as an external air curtain that further helps in reducing the heat transfer towards the building interior. Thus, a vertical green wall system integrated as the external layer of a double skin facade plays the dual role of moderating the building interior conditions while compensating for the negative impacts of mad made highly dense structures and pollution causes by modifying outdoor environments as well.

2.6 The concept of vertical greenery

Using the cooling potential and thermal capacity of vegetation in moderating indoor environments is not a new concept. Since past vegetation has been used in different means such as in court yards and green envelops in different parts of the world. Earliest example for green facades has been found from Mediterranean region about 2000 years ago whereas Tigris and Euphrates civilization claims for initial development of roof gardens as per the historical evidence. In Northern Europe number of examples for green envelops have been found which dated back to 18-19th century (Kohler, 2008; Dunnet & Kingsbury, 2008). As Kohler (2008) highlights during the period of 1880-1940 approx. two hundred articles on green facades has been published from which nineteen articles have focused on green roofs and others on backyard green coverage with new flower species. Early literature suggests that the concept of vertical greenery has been familiar to Europeans and studies have been conducted in English and German.

2.6.1 Evolution of vertical greenery

Even though the concept of sustainability is widely discussed all over the world, humans' rush to achieve unyielding development has ignored the benefits and importance of sustainability. Due to this reason all means of pollutions; namely land, air and sound are taking place harming mother nature and unbalancing the natural equilibrium needed for survival of living beings. In such a situation the need for sustainable approaches and interventions in multidisciplinary areas has become vital resulting the emergence of green facades. At the initiation, greening building facades, green roofs and terraces came into practice extending the trend to vertical greening where vertical facades of buildings too were converted into green facades.

The vertical green façade systems were introduced as a useful element in buildings for thermal regulations and energy saving (Kohler, 2008). In the simplest form of explanation vertical greening is plants grown on vertical surfaces. As Shiah & Kim (2011) states vertical greening can be constructed outside or inside walls integrating one or more plant types to stand independently or to provide structural support to the walls attached. The terminology related to vertical greenery varies from Vertical Green

Systems (VGS), green walls, vertical gardens, bio shader, green vertical systems, green facades, vertical landscaping and etc. (Safikhani et al., 2014; Perini et al., 2011a; Wong et al., 2010a).

2.6.2 Trends of vertical greening integration

Interest on integrating vegetation in building design is becoming more popular whereas more researches are carried out to evaluate the positive impacts of such methods. According to Perini (2012) architectural publications on vegetation integration has significantly increased in numbers from year 2005-2010 signifying the increased interest on building designers on vertical greening. The interest on integrating vegetation on building facades can be related to the growing need of sustainable approach which improves the efficiency of building and environmental conditions as well to the intention of showcasing such projects as “green” while adding an aesthetic value.

By today façade greening has become a fast-growing research interest in world based on the architectural and aesthetical values they offer along with the potential building performance improvements and reduction of buildings’ impact on environment (Ibraheem et al., 2017). A Safikhani et al., highlights implementation of VGS has become a highly adopted green technique due to its numerous benefits related to environment, ecology and economic advantages. Designers have devoted this concept to move to a paradigm of environmentally friendly building (Köhler, 2008). This can be seen in North America, Japan (Hoyano 1988), Africa (Holm, 1989) Canada (Wong et al., 2010a), Thailand, Chicago and recently Asian countries as well.

2.6.3 Insight to vertical greening systems

By today different vertical greening methods have emerged with various characteristics varying from plant types, growing medium, layers included in the system, method of maintaining and etc. Depending on these characteristics the cooling potential, aesthetic aspect, insulation properties and life cycles varies. From a functional aspect, vertical greening systems require more complex designs compared to other typologies of integration, which requires to consider number of key variables (Perini et al., 2013). In terms of function vertical greening require a complex design considering several variables. Different green façade systems are available with or without windows, with a simple disposition of climbing plants at the base of the façade. Shrubs in different sizes in planter boxes fixed to a structure are also used to cover vertical walls whereas thin panels fixed to vertical structures with different plants too are used as a wall covering. As per the literature vertical greening is classified mainly into two categories based on the growing and construction method used (Figure 2.5). The two types are façade greening and living wall systems.

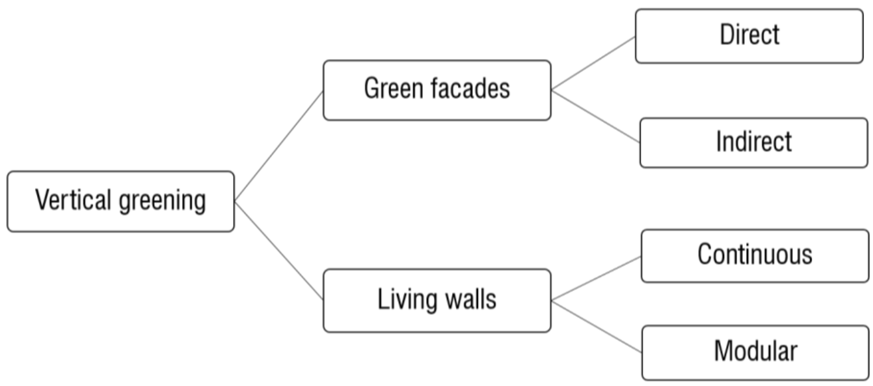


Figure 2.5: Vertical greening classification based on the construction method

Green facades can be further categorized as direct green facades and indirect green facades based on the location of the plants. In direct green façade plants are directly attached with the vertical wall surface and in indirect green façades self-clinging climbers are attached to support structures along the vertical wall (Hunter et al., 2014; Manso & Castro-Gomes, 2014). In green facades climbers are attached to building vertical surface either directly or supported by trellis, cable, mesh and many such materials (Figure 2.6). Here the climbers are planted either on the base of the building closer to the building edge or in different levels closer to the facade (Perini & Rosasco, 2013). The growth media too is placed in different methods based on the green wall type. In green facades growth media is placed on the ground whereas in modular living walls it is placed vertically in front of vertical surfaces (Perini *et al.*, 2011b). These are also identified as facade greening, carrier system / bio – walls (Safikhani *et al.*, 2014; Badrulzaman *et al.*, 2011; Perini *et al.*, 2011b).

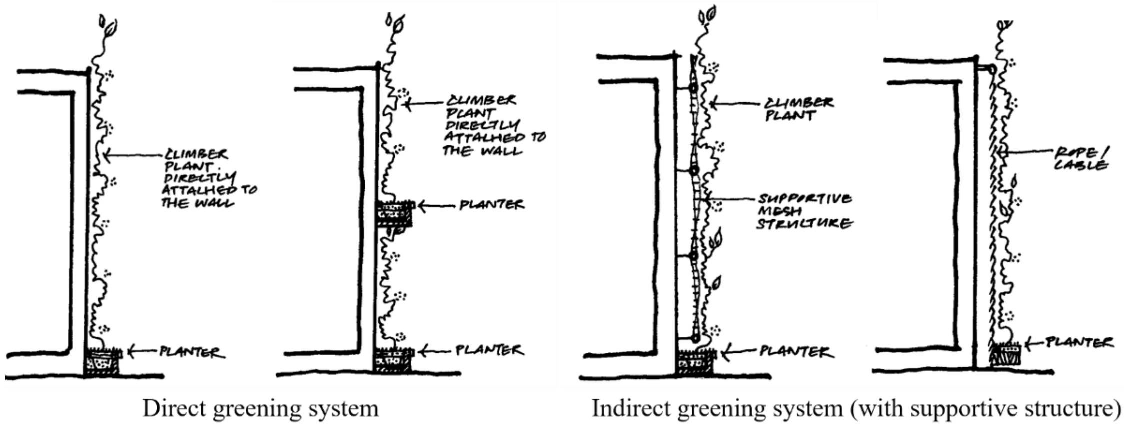


Figure 2.6: Green façade typologies

Living walls too can be categorized as continuous or modular (Manso & Castro-Gomes, 2014). In living wall systems also known as vertical gardens or green walls, different shrubs grown in modular panels using different growing mediums are used to cover the vertical walls (Figure 2.7). In practice materials like felt, mineral wool, felt and foam and etc. are used as artificial growing mediums as alternative for soil. In this system, to provide plants with the water and nutrient requirements hydroponic cultures and watering systems have been developed accordingly.

Since Living Wall Systems (LWS) have the potential of using different types of shrubs that don’t grow vertically in general, the opportunity of enhancing the aesthetics of the green façade is higher. Several LWS types can be identified depending on the panel type and material and growing medium.

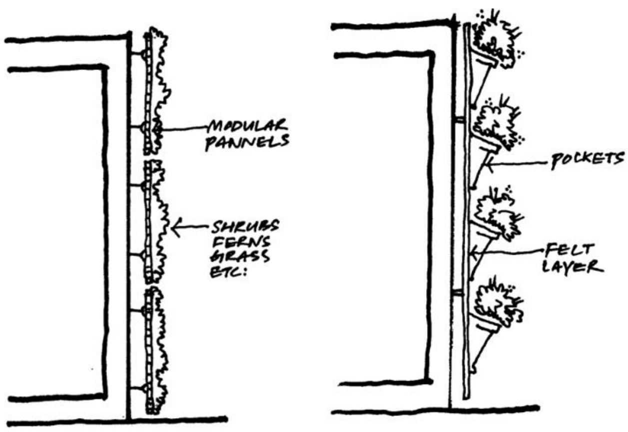


Figure 2.7: Living wall typologies

2.7 Vertical greening based research studies

The integration of vegetation is a continuously growing research field where the interest on the novel vertical and horizontal greening systems of related professionals is ever increasing. Further, the number of publications and researches conducted to assess the positive effects of vegetation to improve the environmental quality too has increased. Integration of green facades with buildings is rapidly developing in the field of architecture, due to the aesthetic and sustainable benefits they offer. However, many of the published articles emphasize on green roofs than vertical greening highlights the benefits and effects of vegetation on urban climates and buildings (Wong et al., 2010).

Beside the positive impacts of green on the visual comfort for human, green facades further influence the microclimate of a place and helps improving the livability by increasing ecological value, mitigating heat island effect, insulating properties and improving air quality. With the increased focus on sustainable design to mitigate the adverse effects of buildings on the ecology, the attention is now directed more towards integrated solutions. Here, green envelops become one promising option. According to the USEPA the strategies for green buildings not only represents sustainable materials in construction, but also utilizing natural processes such as shading effects of trees, insulation capacities of green facades, mitigation of urban heat due to evapotranspiration and etc. (USEPA,2010). Greening the exterior facades grants numerous ecological and economic benefits including energy conservation, storm water management and etc. as well as providing a more aesthetically pleasing environment in which to work and live.

2.7.1 Performance based analysis of VGS

Many researches have been conducted in international context in categorizing vertical greening and analyzing performance on improving building interior as well as outdoor environments (Manso & Gomes,2015; Loh, 2008; Jim, 2015). Though not directly related to vertical greening, research on effect of vegetation to building performance has been done for many years. A study done based on USA, residential building energy consumption shows a 60% energy saving due to cooling potential in during summer days by introducing plants next to buildings (Parker, 1987) whereas a study done by

Hoyano (1988) has revealed up to a 18^{0}C reduction of wall surface temperature on a west facing wall covered by Ivy.

A dynamic module using computer was established by Holm (1989) to simulate thermal effects of exterior evergreen and deciduous plant cover on building interior which showed a reduction of summer temperature in indoors up to 5^{o}C. Di & Wang (1999) and Cantuaria (2000) has shown 8-10^{o}C lowering of indoor temperature due to vegetated walls compared to plain walls. Available research evidence signifies the benefit of vertical greening in cutting off solar heat gain to building interiors. However, majority of researches are short term based and long-term data analysis to incorporate in detailed thermal analysis is less. Further, the systems for the integration of vegetation are not yet fully accepted as an environmental quality restoration and energy-saving method for the built environment, due to the data scarcity which is required to quantify their effects and to assess the real sustainability aspects. Similarly, a large number of researches has been conducted in many parts in the world to assess the environmental benefits of vertical greening aiming at different aspects such as heat reduction, dust control, noise and air pollution control and etc.

a) Thermal benefit of VGS

Among the numerous benefits related to vertical greening, temperature reduction due to the shading and cooling effect is highly discussed. Previous research provides evidence for benefits of green roofs on the reduction of inner temperature of buildings which was found to be 3-4^{o}C lower than the outdoor temperature (Peck et al., 1999). In the research done by Kenneth et al (2010) to quantify the solar intensity reduction of different layers of leaves and total shading co-efficiency has been experimented using a canopy of a vertical deciduous climber. As per the results obtained by Wong et al., (2010a) from the study done using a VGS at an initial stage in Singapore, a maximum of 11.58^{o}C surface temperature reduction has been recorded by a modular living wall with a mixed substrate grid in comparison to the control bare wall.

Another research carried out in Singapore has used eight different vertical greening systems to evaluate the thermal benefits in tropical climates. The results indicate that all the systems are beneficial in reducing building surface temperature in varying degrees as per the vertical greening type which leads to reduce cooling loads thus reducing energy consumption (Wong et al, 2010). As Ibraheem et. al, (2017) highlights the inclination angle of the green façade impacts on the light availability by cutting off direct natural light which in turn can cause increased energy consumption for artificial lighting. The results indicate inclination angle more than 60° can significantly block the natural light intake to building interior.

b) Benefits of VGS in urban context

Green integration for building facades is identified with many environmental related benefits as well. Mitigation UHI, control of urban temperature, reduction of air pollution by reducing particulate matter and disposition of aerosol, noise attenuation, health improvement etc. are identified as such benefits (Sheweka & Mohamed, 2012). Alexandri & Jones (2008) reports green walls and green roofs as the resources to mitigate the rise of temperature inside urban canyon (Figure 2.8). Here, nine case studies done in different contexts have reported considerable temperature reduction.

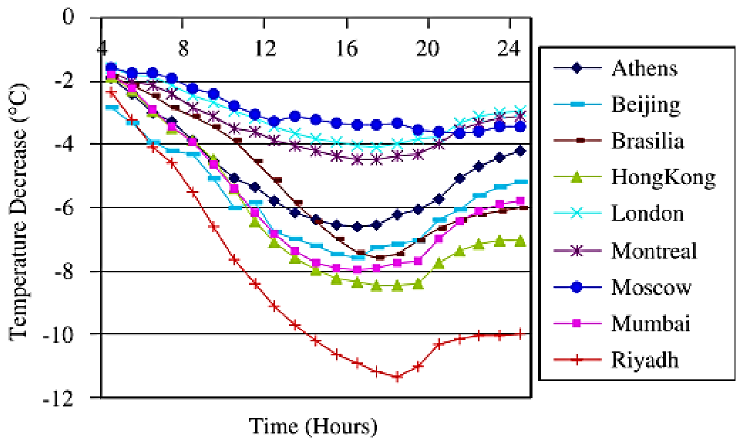


Figure 2.8: Urban canyon temperature behavior with different green interventions

Source: Alexandri & Jones, 2008

A study done at a high-rise building of twenty-one stories in Penang, Malaysia to check thermal comfort parameters by measuring solar radiation, air temperature, humidity and wind velocity of different landscaped gardens has revealed a significant difference in each parameter in each garden. As kohler (2008) states the thickness and the mass of vegetation in the green façade has a greater influence in the potential benefits. Average surface temperature reduction of 5.5°C has been recorded in a vegetation covered wall facing south-west direction with a maximum reduction of 15.2°C in Mediterranean climate during the months of August and September. Perez et al., (2011) further elaborates of the effect of VGS on humidity level due to evapotranspiration and the performance as a wind barrier. A study conducted in Netherlands to evaluate the impact of different VGS on surface temperature and wind current results has revealed no significant effect on wind speed near the VGS surface up to 1m distance while recording a 5^0C surface temperature reduction and a 1.1°C average cavity air temperature reduction (Perini et al., 2011).

Kohler (2008) highlights the potential dust trapping by VGS in urban contexts highlighting the benefit of mitigating the air pollution. Ottele et al., (2010) further confirms this by stating the particle adherence of VGS and efficiency in absorbing the air pollutants and particulate matter such as CO_2, nitrogen oxides ($NO_{x)}$ and sulfur dioxide (SO_2). Noise attenuation too has been studied as another benefit related to VGS in urban contexts by numerous studies conducted in controlled conditions highlighting the positive contribution of VGS as an acoustic barrier (Azkorra et al., 2015). Even though the diverse results of different studies do not give a direct value of the noise reduction Lunain et al., (2016) signifies the ability of the plant substrate and foliage to absorb and scatter the sound with the findings obtained from the study done in France using a constructed VGS. Further to these environmental related benefits the positive impact of VGS application in urban contexts to the general health of urban residents too has been identified. Here a positive relationship is established between the percentage of greenery in living environment and the health condition of people (Maas et al., 2006). As highlighted by Maas et al., (2006) city planning regulations and policies should adopt green integration due to many benefits in urban contexts.

2.7.2 Research context of VGS in local scale

The number of researches conducted related to VGS in tropical climates is significantly less compared to research evidence on positive effects of VGS in European context and information on systems and applications (Herath et al., 2016) focusing temperate climates. The available studies are limited to Malaysia, Singapore, Thailand and some south Asian countries and mostly are either experimental or simulation models. In the review by Safikhani et al., (2014) out of the identified seven real case studies, four cases are related to tropical contexts. Wong et al., (2010a) states the benefits of VGS in tropical context has been proven using two to three application from which are mostly done under controlled conditions.

Several urban vegetation related studies have been conducted in local Sri Lankan context where amplification of air quality and comfort by green roofs (Nisansala & Halwathura, 2011), spatial and temporal changes of the green cover of Colombo city (Wickramasinghe et al., 2016), urban green cover protocol to reduce urban heat island in Sri Lanka (Asmone et al., 2016) and urban green space standards of Colombo (Li & Pussella, 2017) can be identified as significant studies. However, very few studies have been conducted in local context focusing on VGS. The study by Jefas & Silva (2013) conducted in Colombo has measured the surface temperature of walls shaded by vertical greenery in multi-story buildings using two case studies which has resulted an average surface temperature reduction of 3.14ºC compared to a bare wall. Another study which has evaluated the surface temperature reduction from VGS using three case studies where two cases were from Colombo and the other was from Matale has recorded 3.5ºC, 3.4ºC and 3ºC of reduction (Peiris et al., 2014).

2.8 Chapter summery

Extensive energy use for human activities has led to the current global warming crisis and buildings play a major role as a contributor for the phenomenon. Researches around the world are focusing on different approaches on this regard with the aim of mitigating the causes of the global warming scenario. Reduction of energy consumption mainly for comfort requirements is feasible with proper passive design application to buildings from the design stage itself. As the building envelop is the main component of the building that interacts with the climatic factors outside, treating building envelop to reduce the intake of unfavorable conditions to building interior is vital. However, the requirement for and the advantages of environmentally friendly buildings in the context of sustainability is not to be doubted. Building façade which is the largest building envelop component can be designed to act as a climatic filter to avoid the intake of unfavorable climatic impacts whereas proper design of internal arrangements and sectional form provides the opportunity to maintain comfortable indoor environments.

Integration of double skin facades therefore is a sustainable and passive envelop design intervention.

Integrating vertical greenery as the external skin of the double skin envelop can be a promising intervention to make buildings energy efficient and environmentally feasible while offering many benefits to urban contexts as well. Existing research studies indicate the building scale and urban scale benefits of vertical greenery systems in terms of minimizing heat gain, energy saving, mitigating noise and air pollution and etc. When considering the functional aspects vertical greening systems require complex design approach. Characteristics of vertical greening systems, materials used and etc. determines the influence of the system in terms of performance either positively or negatively in improving building envelop behavior, moderating the outdoor climatic conditions and the life cycle of the system itself.

Based on the findings from the available literature it is evident that, to uncovers the ecological, energetic, hydrological, psychological and related environmental properties of green wall types more researches are need to be conducted on green wall performance, ecosystem service valuation and tool development, design parameters (plant selection, materials, soils), management, ancillary benefits to local environments and many more. Developing this knowledge will increase the viability of green walls and their acceptance by the public as truly sustainable technologies. Therefore, the research aims at addressing the identified gaps and look into green wall performance, design parameters (plant selection, materials, soils), management, ancillary benefits to local environments through the objectives formed.

3. PUBLIC & DESIGNER PERCEPTION ON VERTICAL GREENING

3.1 Introduction to the chapter

Global warming became significant in last century drawing man's attention towards sustainability necessitating returning back to nature. Need of compensating for the destroyed green cover for built contexts by replacing greenery has been identified as vital which demand promoting greenery specifically in highly urbanized and populated contexts. With the increasing number of buildings in an urban context inclusive of high rises, area of building envelop that interacted with the surrounding too has increased. Thus, the vertical surfaces of buildings were identified as an opportunity to link the urban areas with nature by promoting vertical greening. The concept of vertical greening has been in practice for many decades. Yet the popularity reached a peak state when this concept was identified as an ideal method to increase urban greenery. This research aims at identifying the benefits of vertical greening in local context and to propose a vertical greenery system. Therefore, obtaining a better idea on the perception of the concept of vertical greenery is needed. This chapter focus on identifying the perception of public and designers on integration of vertical greening in local context.

3.2 Vertical greenery in Sri Lankan context

Number of cities around the world have already started vertical greening projects in urban scale whereas integrating vertical greening in individual buildings too is being put into practice. The vertical greening trend is being embraced by the Sri Lankan urbanities as well in present context and is being popularized in high rise commercial buildings in an especially in Colombo context. However, VGS integration in local context seems to be in a primary stage. Despite this trend general public still show a reluctancy to integrate vertical greening to their individual residences or built forms. Hence, it was identified as a need to investigate the perception of general public and building designers on the concept of vertical greening in the local context. Therefore, three separate questionnaire surveys were conducted aiming public, building occupants and designers (Figure 3.1). The questionnaires were pre-tested for their variation, flow, question order, understandability, time duration and appropriateness based on expert review.

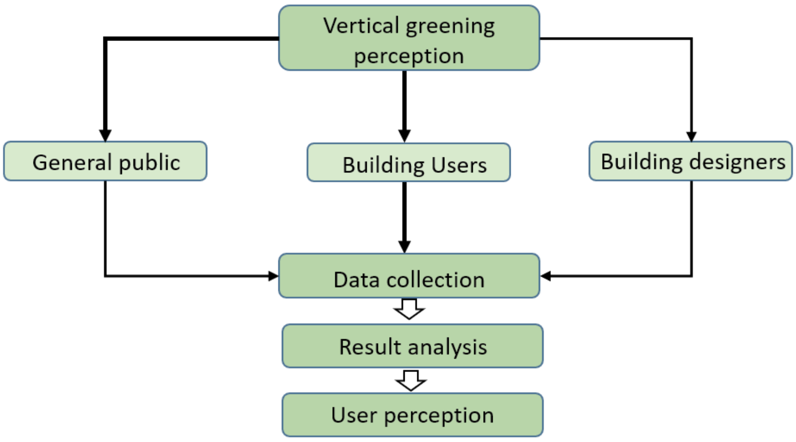


Figure 3.1: Procedure of the questionnaire survey analysis

3.3 Perception of general public on vertical greening

The survey was conducted in a hybrid mode as an online survey as well as using randomly selected daily commuters of Colombo area. The questions were composed in simple format that could be easily understood. The focus of questions was to assess how the public would grasp the concept of vertical greening as a sustainable solution for current environmental issues (refer appendix A). The questionnaire represented six major sections;

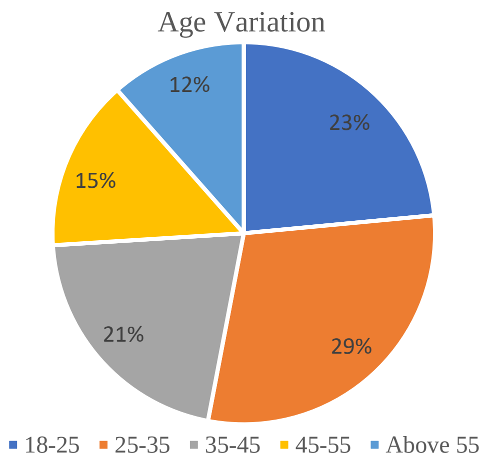
- Personal details (Question 1- Question 2)
- Personal observation (Question 3- Question 6)
- Personal opinion (Question 7- Question 9)
- Personal preference (Question 10- Question 12)
- Personal application (Question 13- Question 17)
- Overall idea (Question 17 – Question 20)

3.3.1 Selected sample

A group of 130 randomly selected sample from Colombo area was given the questionnaire from which a convenient sample of 100 was considered for the evaluation whereas a sample of 100 was selected from the online survey with the aim of obtaining an unbiased response. The final convenient sample taken for analysis was 200.

3.3.2 Response analysis of perception of general public on vertical greening

From the selected sample 29% majority represented the age group of 25-35 and a gender variation of 56% male and 44% female (Figure 3.2).



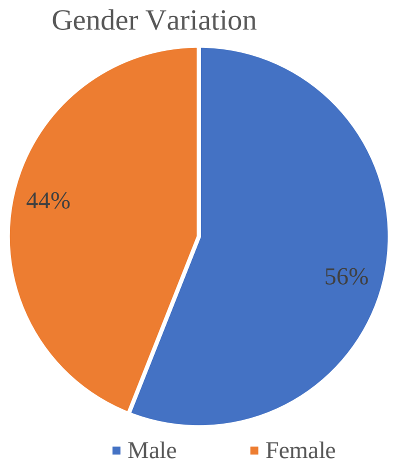


Figure 3.2: Age & gender variation of sample

a) Personal observations

The section aimed at identifying the attention drawn by vertical greening and the degree of awareness on vertical greening systems. As shown in Figure 3.3 based on the answers given related to personal observations even though a majority (93%) has noticed vertical greening yet a majority (68%) is unaware of its systems and typologies.

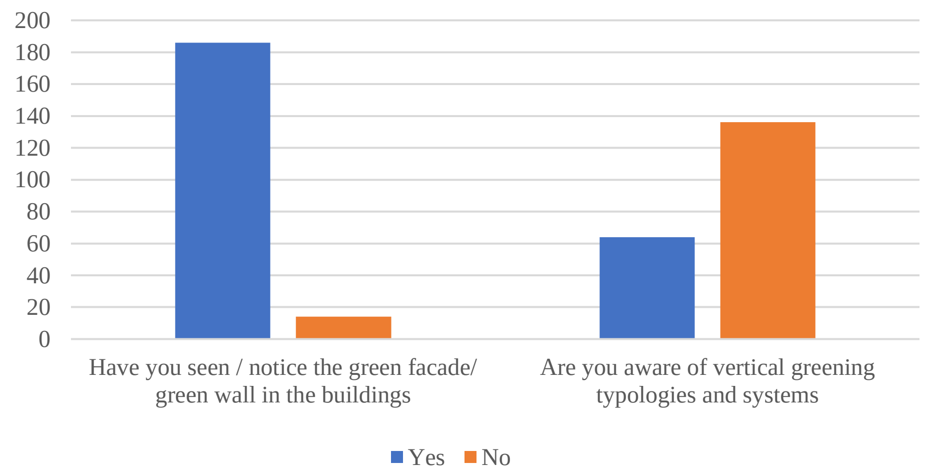


Figure 3.3: Personal observations and awareness on VGS

b) Personal opinion and preferences

Interestingly 100% agreed on the environmental benefits of vertical greening reasoning out the increased biodiversity, urban green spaces, cooling effect, air purification as the main benefits obtained by integrating vertical greening. In evaluating the performance aspects of vertical greening majority 94.5%, 62%, 56%, 59% and 95% respectively strongly agreed that vertical greening add extra beauty to the building, trap dust from outside, block noise from outside, reduce the heat coming from outside and vertical greening is aesthetically pleasing and visually satisfactory (Figure 3.4).

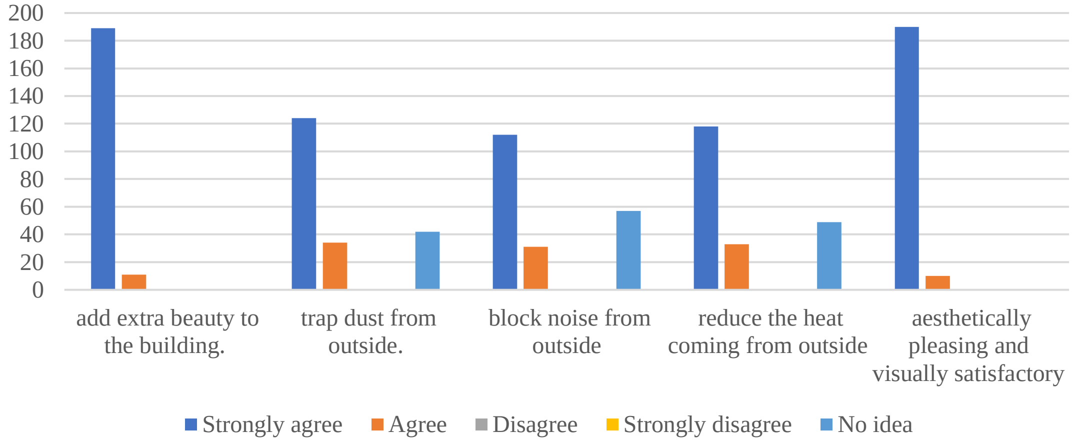


Figure 3.4: Level of agreement on VGS related benefits

As shown in Figure 3.5 a similar result was obtained on the satisfactory level of physical and psychological conditions with the presence of vertical greening where majority were highly satisfied in both ways 92.5% and 96% respectively.

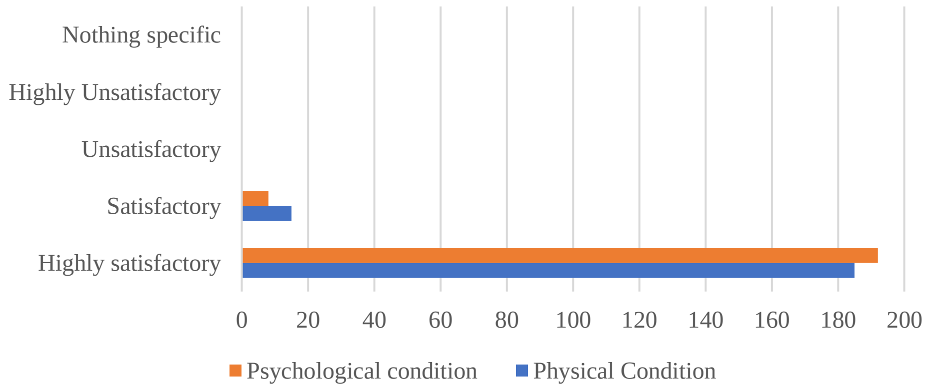


Figure 3.5: Level of satisfaction gained by VGS

However, from the sample only 44 (22%) had seen a building prior to the integration of vertical greening (Figure 3.6). From them 28 preferred the building after the vertical greening integration whereas 10 respondents preferred the building without vertical greening and others had different opinions based on the appearance and building character change occurred due to the green covering.

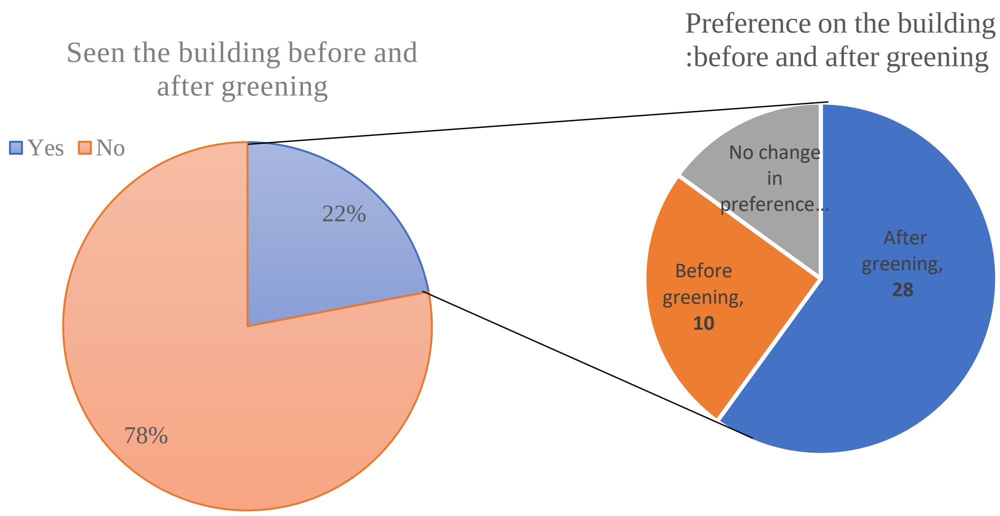


Figure 3.6: Preference of greened façade: before and after VGS integration

c) Personal application

From the sample only six (3%) had a green façade at their own residences and twenty-two (11%) has the experience inside a building integrated with vertical greenery (Figure 3.7). Improvement of thermal comfort, visual comfort, physical comfort and all integrated benefits were given as the reasons for the six respondents to have vertical greening at their residences.

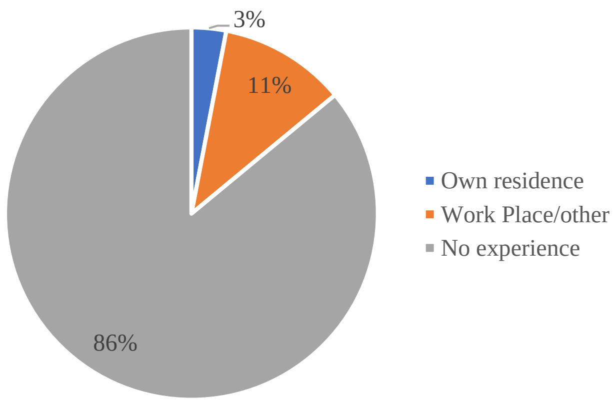


Figure 3.7: Experience of green integrated spaces

As shown in Figure 3.8, 90% of the respondents preferred to have a green façade at their residences based on the reasons such as aesthetical enhancement, fresh air, heat gain reduction and their integrated benefit. However, noise attenuation was not identified as a benefit by any of them.

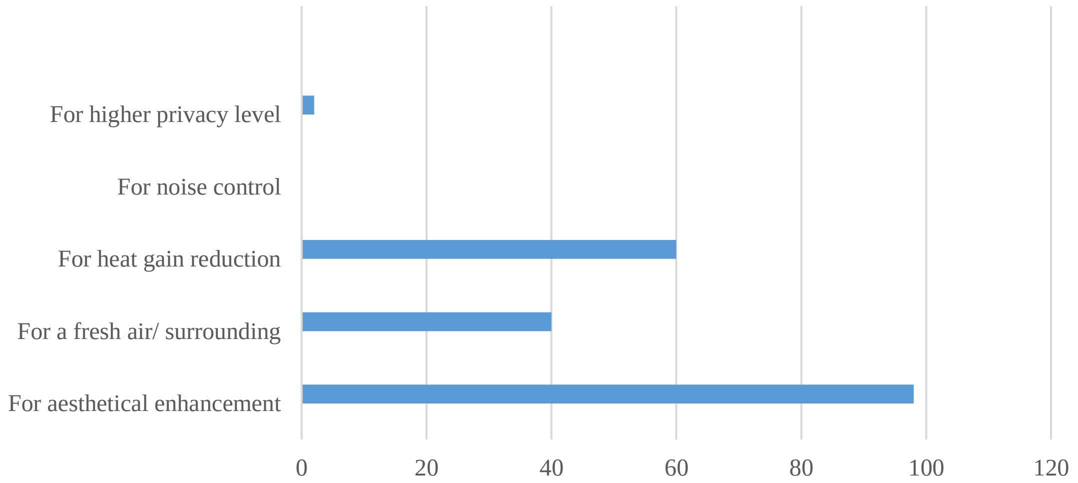


Figure 3.8: Reasons to prefer vertical greening

Respondents who didn’t prefer having a green façade reasoned out higher initial cost of construction, no space for vertical greening integration (Figure 3.9). Further high cost of integration, maintenance, pest control and damages to building exterior were given as the main issues related to vertical greening.

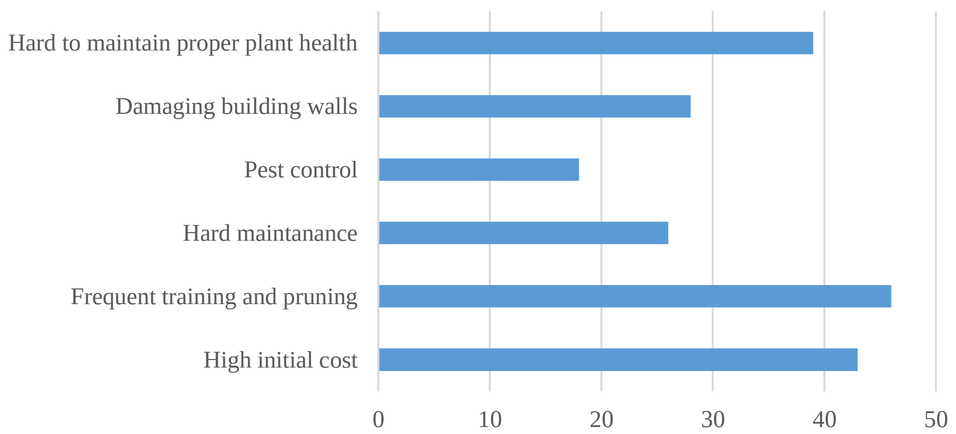


Figure 3.9: Reasons for not preferring vertical greening

However, 94% of the respondents have agreed upon integrating vertical greenery as a sustainable development solution (Figure 3.10). Main reasoning given for this was the aesthetic enhancement as well as the opportunity to increase greenery in urban contexts.

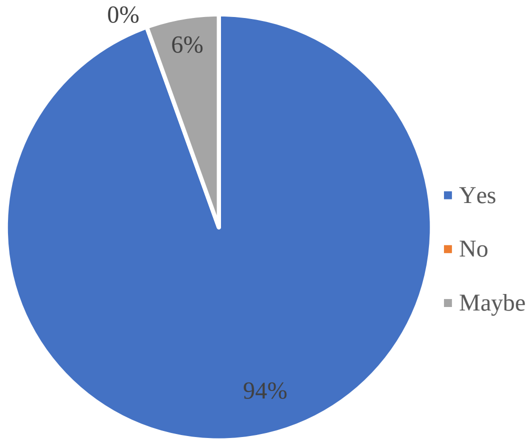


Figure 3.10: Opinion on sustainability of vertical greening

3.4 Occupant satisfaction on vertical greening

This section aims to evaluate the perception and satisfaction of the occupants of buildings with vertical greenery. Permanent workers in buildings identified with VGS were selected as the audience for the survey to identify the attention drawn by the vertical greening system and to evaluate the degree of awareness on the functions of vertical greenery systems. Survey was conducted in person using convenient sampling method. Similar to the general public perception survey the questionnaire was prepared under five main sections (Refer appendix A) which was developed with pre-testing and expert review.

- Personal details (Question 1- Question 3)
- Personal observation (Question 4- Question 6)
- Personal opinion (Question 7- Question 13)
- Personal preference (Question 14- Question 17)
- Personal application (Question 18- Question 21)

3.4.1 Selected sample

From the selected buildings 150 convenient sample was selected to evaluate the responses. Questionnaire was distributed in person to staff of the buildings in different working levels. Major characteristics of the considered sample was consisted with age variation, gender variation and the occupants’ service/ residence time period in the building. Figure 3.11 shows the gender variation of the considered sample which consisted with 57% male participation and 42% female participation, age variation and occupant service time variation of the selected sample.

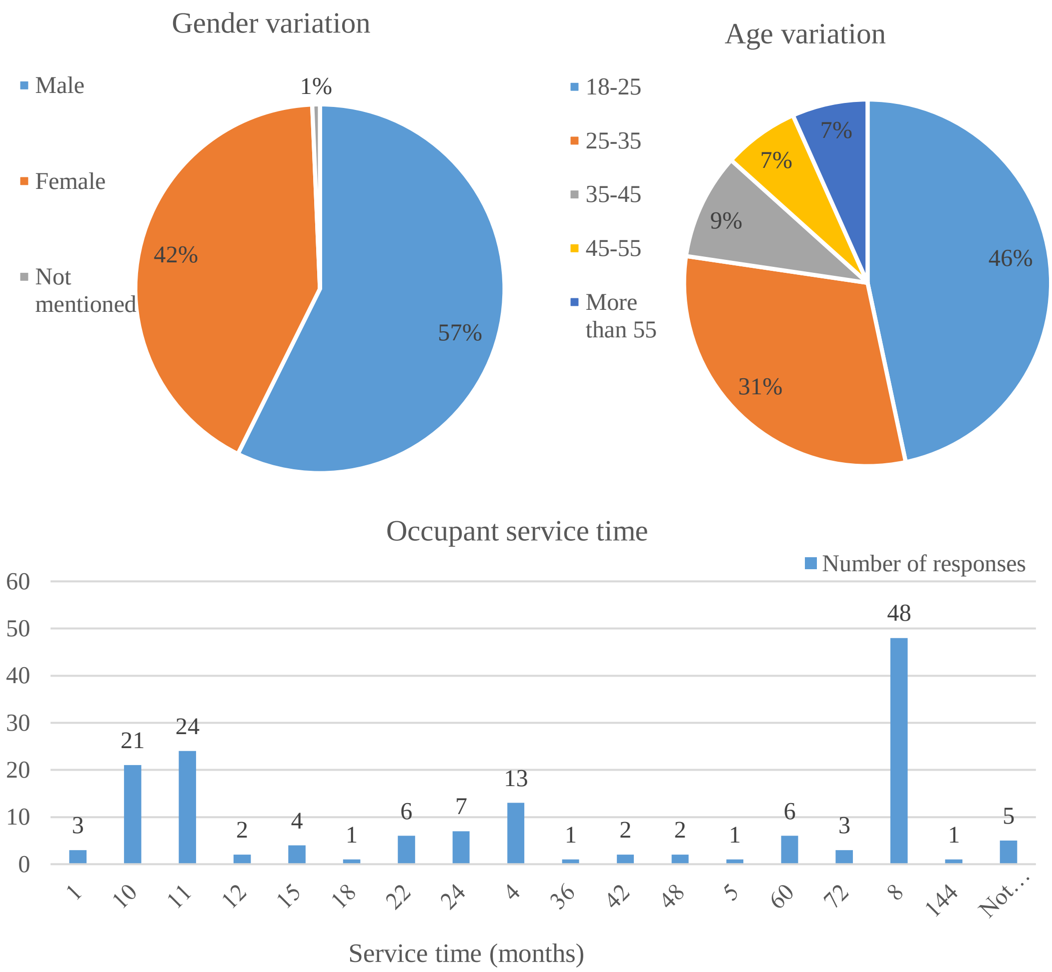


Figure 3.11: Gender variation, age variation and occupant service time

3.4.2 Analysis of occupant satisfaction on vertical greening

Ninety nine percent (99%) of people (149 out of 150 sample) had observed the green façade at the building emphasizing the high aesthetic appeal of vertical greenery systems in urban environment. Based on their opinion visual appeal, shading, control of temperature, mental relaxation, dust and noise control and air quality improvement were obtained as the purpose of constructing a green façade at the building.

a) Personal observations and opinions

As depicted in Figure 3.12 majority of the responses (46%) identify the beautification as the main purpose of vertical greening followed by the control of temperature (21%) and shading (8%). Results signify that most of the respondents were aware of the aesthetical value of vertical greening systems. Yet, only a minority (20.5%) of the occupants had the idea of thermal regulation potential of the green walls.

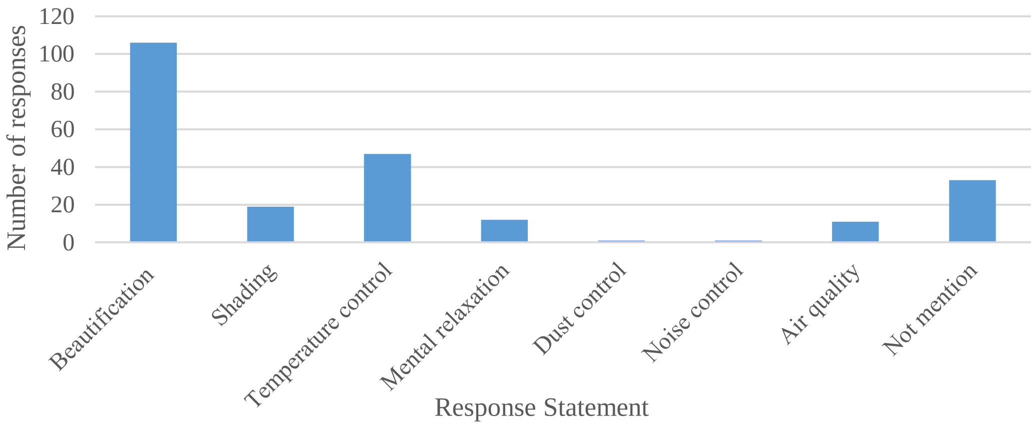


Figure 3.12: Identified purpose of vertical greening

Occupants' agreement on functions of vertical greenery systems and their level of agreement are presented in Figure 3.13 where 52% strongly agreed on the aesthetical enhancement obtained by green façade to the building, 19%, 10% and 30% respondents strongly agreed with dust, noise and heat control obtained by the VGS respectively. Total of 95.3% people had a positive opinion on the statements of vertical greenery system functions. Noise attenuation potential of green façade was least identified by the respondents and it is observed that 41% of the respondents were neutral on their opinion. It can be argued that occupants may not identify the possible noise reduction by vertical greenery systems due to higher noise levels in the Colombo area when compared to rural environment. The aesthetic enhancement by the green façade is the most popular purpose of VGS as recognized by the society.

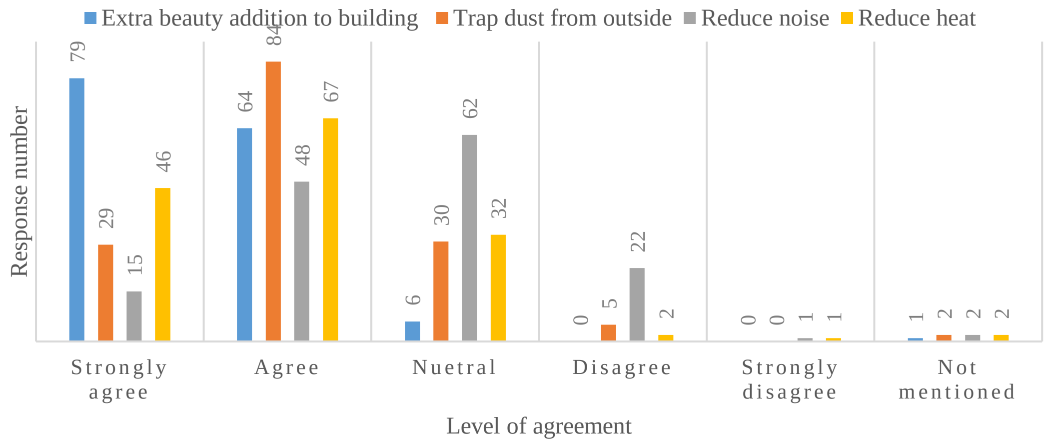


Figure 3.13: Occupant agreement on vertical greenery functions

b) Occupant opinion on comfort factors related to VGS

Under this section thermal comfort, psychological comfort and visual comfort near the vertical greenery systems, light levels and the temperature behavior at due to VGS were evaluated according to satisfaction level of the occupants. When considering the responses, as depicted in Figure 3.14, 34%, 49% and 45% occupants were very satisfied with thermal comfort, mental relaxation and visual comfort respectively.

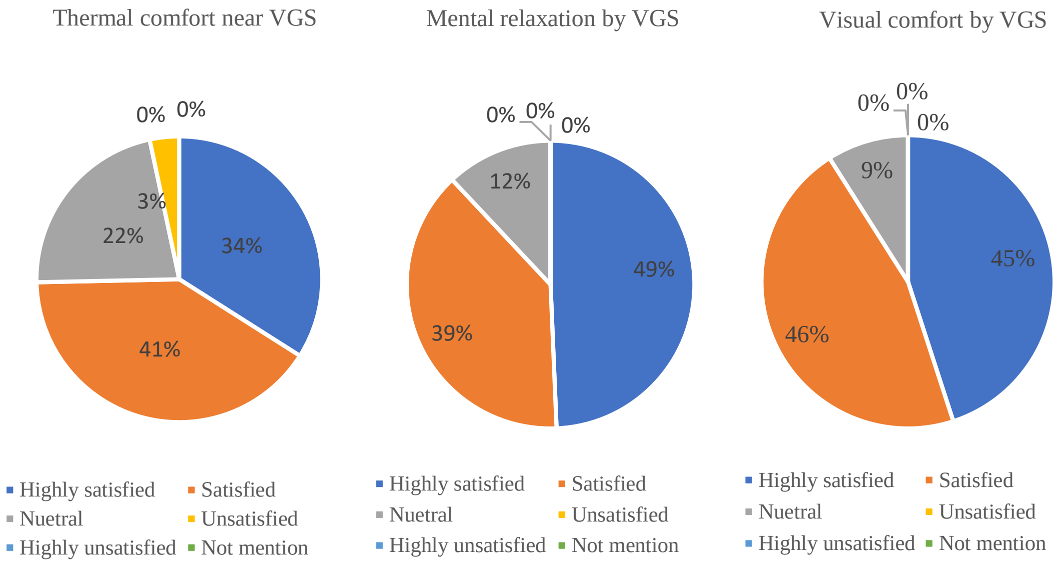


Figure 3.14: Occupant opinion on comfort factors near to VGS

c) Personal preference and applications

According to the results of the questionnaire survey, 57% of the building occupants were directly sheltered from the building green façade and 42% occupants were not directly sheltered from green façade. Figure 3.15 illustrate the satisfaction in percentages for light penetration and heat reduction where 11% and 30% occupants were highly satisfied and satisfied with heat reduction respectively, whereas 17% of the occupants were neutral in their opinion. Only 6% were highly satisfied with the light level transmitted through vertical greenery systems.

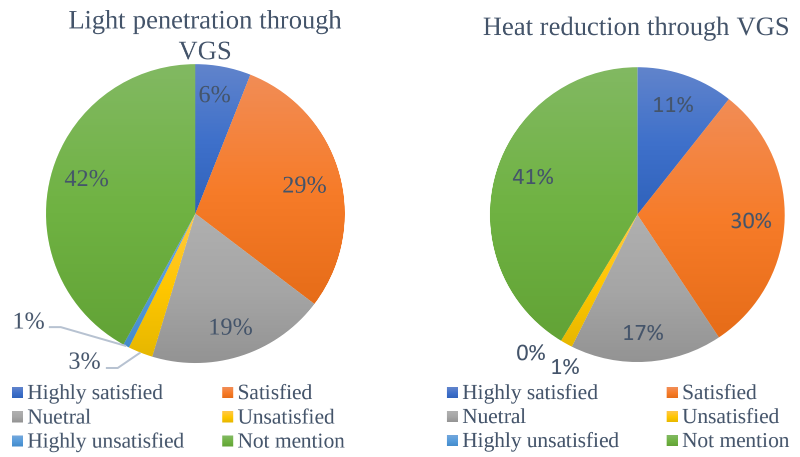


Figure 3.15: Perception on light penetration and heat reduction

d) Personal preference and applications

Twenty percent (20%) of the respondents were working in the same building prior to integrating the vertical greening systems and 80% out of them preferred the building appearance after vertical greening integration (Figure 3.16).

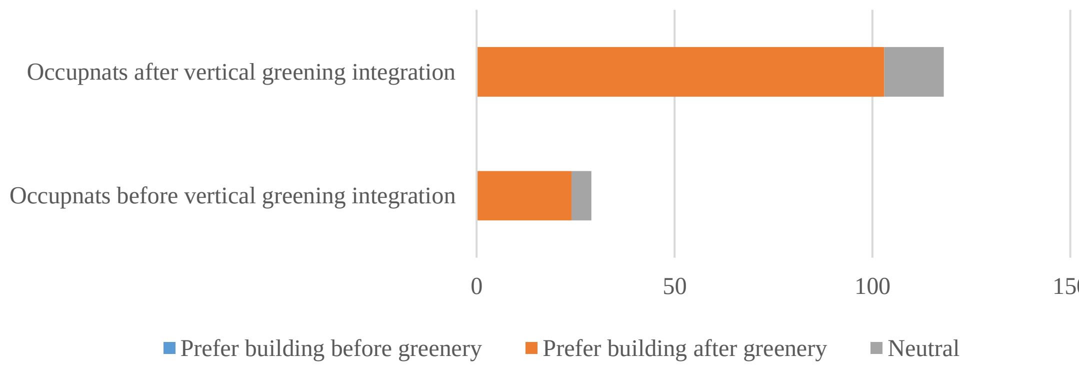


Figure 3.16: Preference of vertical greening: before and after VGS integration

Seventy eight percent (78%) building occupants were not occupied in the same building before constructing the green walls. However, 87.3% of the occupants who joined after the vertical greenery preferred the vertical greening integration. Higher property value and enhanced appearance of the building, provision of fresh air and improved scenic view were gained as reasons for the preference on building with VGS highlighting that it has led to a better working environment for the occupants.

As indicated in Figure 3.17 majority (79.3%) of the occupants did not have a vertical greenery system at their residences and 78.7% of the occupants had a preference to integrate a greenery system at buildings they work or live in; highlighting their positive perception towards the green walls.

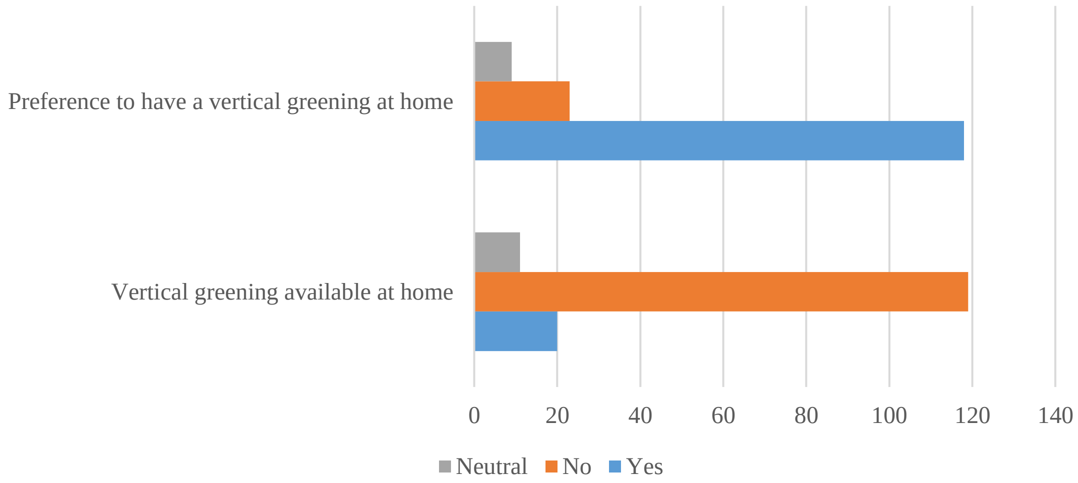


Figure 3.17: Occupant preference to have vertical greening at own residence

The key reasons which inspire the positive perception on VGS were listed as enhanced aesthetical value due to green wall integration, thermal regulation, air quality improvement and noise level control. According to the survey results as presented in Figure 3.18 (a), the majority (46%) of occupants preferred a green wall due to its aesthetical value followed by fresh air provision (28%), heat reduction capability (26%) and last for noise reduction control. Figure 3.18 (b) depicts the response percentages for limitations in practical application of the green walls. Higher costs of VGS construction, difficulties of maintenance, insects, pest and health related problems (allergies) were listed as the reasons which impedes the integration of vertical greenery systems at their own residences. 36% of the occupants stated the high cost of construction as the main reason and 24% stated difficulty in maintaining the VGS as the limitations of practical application of VGS.

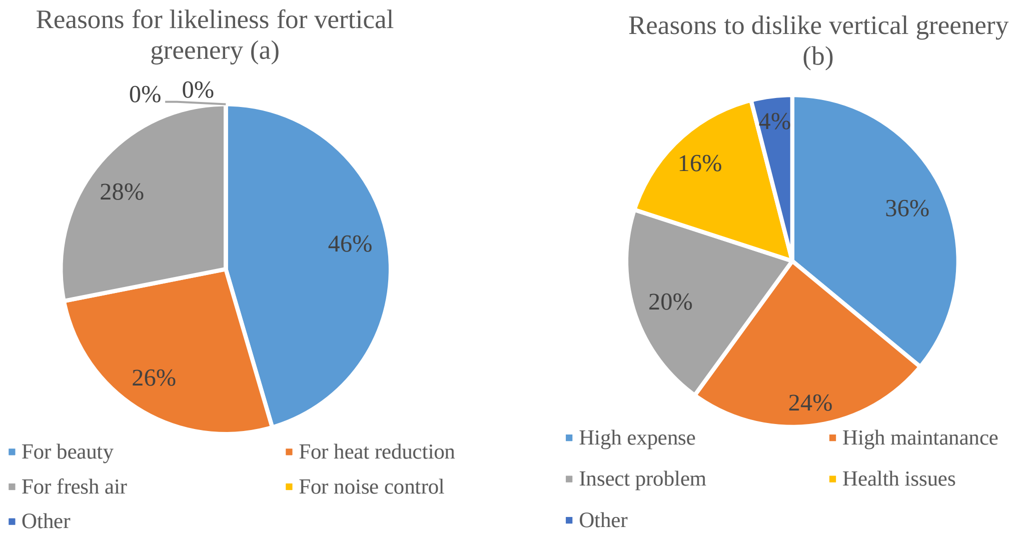


Figure 3.18: Reasons to like and dislike vertical greening

3.5 Designer perception on vertical greening

Concept of vertical greening is being experimented as design integration in many parts of the world by today. Research evidence on the vertical greening related benefits are influencing the design application of VGS. However, based on the observation in local context the vertical greening integration is yet at a primary stage. Therefore, the need to evaluate the designer perception of vertical greenery is identified. Survey was conducted using online platform. The questionnaire was prepared under three main sections (Refer appendix A) which was developed with pre-testing and expert review.

- Personal details (Question 1- Question 3)
- Design considerations and applications (Question 4- Question 12)
- Preference on vertical greening (Question 12- Question 21)

3.5.1 The sample

The questionnaire was sent to 400 practicing architects for which 213 responses were received. From the responses a convenient sample of 200 was selected for the response evaluation. The selected sample consisted of architects of different age groups with varying practice experience in their field as shown in Figure 3.19. 58% majority was female architects whereas 38% majority represented the age group of 25-35 and a majority of 33% represented 10-15 years as the length of practice highlighting a higher response rate from the young professionals in the field.

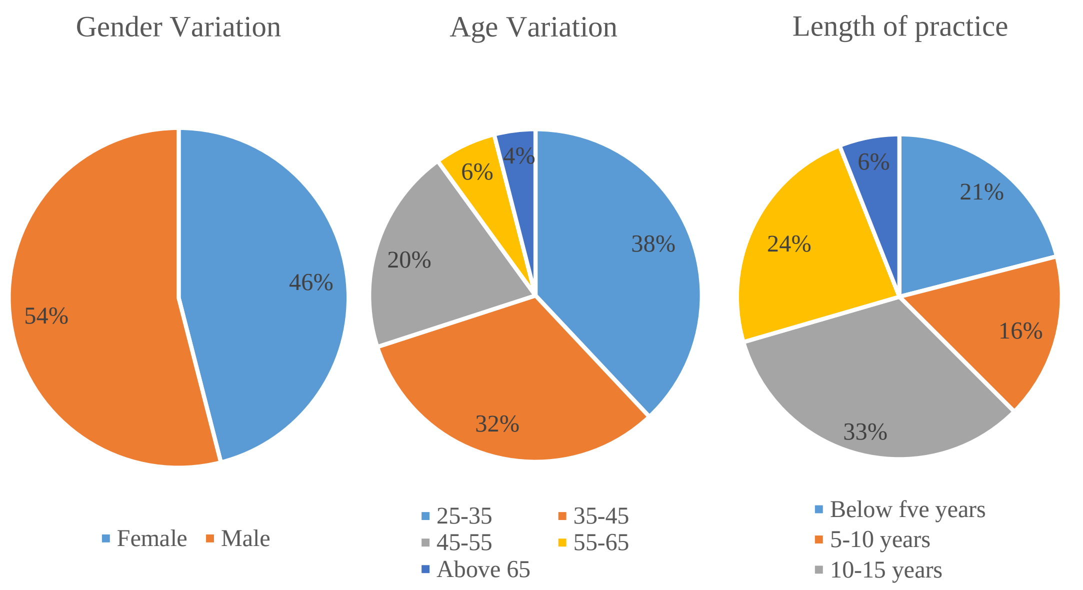


Figure 3.19: Gender variation, age variation and length of the practice

3.5.2 Analysis of designer perception on vertical greening

This section aimed at identifying the perception of architects on the novel trend of vertical greening and related sustainability concepts. Below analysis discuss about the designers' awareness on VGS, preference on vertical greening applications and their client demand for vertical greening.

a) Design considerations and green applications

As depicted in Figure 3.20, 62% of the total participants stated that they consider sustainable design strategies when developing the concept of the design and integrate them into the design whenever possible. However, 14% minority stated as they consider of aesthetics and the requirements of the client and have no specific concern for such sustainable interventions whereas 24% stated that such applications depend on the client, budget, aesthetics and etc and such interventions would be used only in random occasions.

Moreover, a majority of 50.5% and 29% regards vertical greening concepts to be highly acceptable and acceptable respectively with the need of increasing greenery in current global context. While 6% disagrees on this concept 7.5% states nothing specific on the trend and 7% states about both advantages and disadvantages of the vertical greening and its applications.

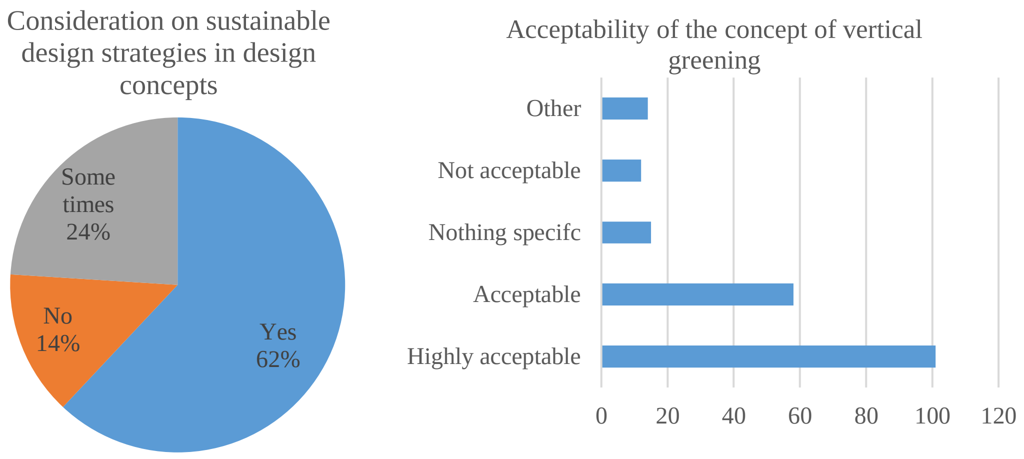


Figure 3.20: Design consideration for green applications

b) Design application of VGS

A majority of the participated architects (81%) have not integrated vertical greening in their designs whereas only 19% have integrated vertical greening or adapted the concept of vertical greening to their designs. However, as depicted in Figure 3.21, 76% would recommend integrating VGS to their future designs. Different reasons varying from sustainability to aesthetics was given for the preference to integrate VGS in future designs. Interestingly none of the respondents stated they would not integrate vertical greening while 24% would recommend based on the design approach in each situation.

One interesting point noted here is that from the 19% of the architects who have integrated VGS to design have done so mainly for commercial buildings. Also, on the other hand the potential gain of points when applying for green rating for buildings by having vertical greening has been one major attraction to integrate vertical greening to commercial buildings. Nevertheless, in terms of client satisfaction application of VGS has been positive as 100% client satisfaction has been achieved in each case.

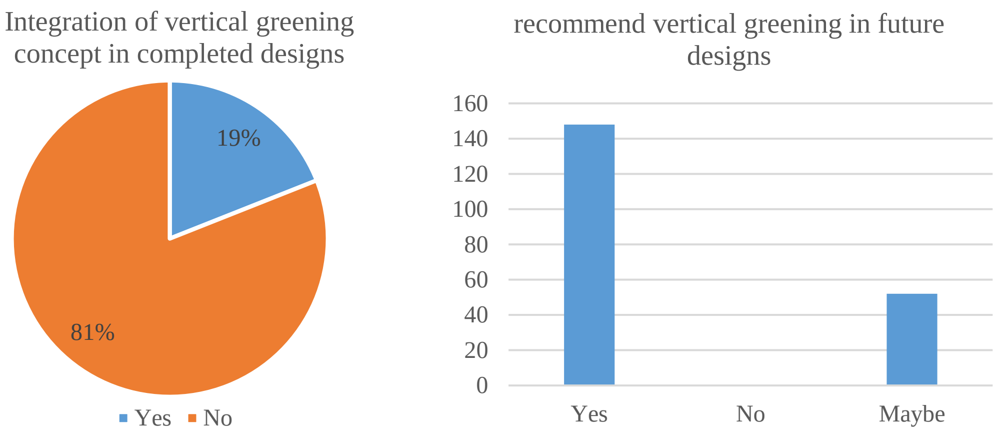


Figure 3.21: Application of VGS in design

In terms of detailed studies or research on vertical greening 51% representing the majority have not done specific study on the vertical greening applications or on their benefits whereas 21% have come across details and information on the area even though they have not specifically conducted any research or study. However, 28% have conducted at least a brief study on the subject area either for knowledge base or with the intention of applying the theories in designs practically (Figure 3.22).

Majority of the 28% however belonged to age groups of 25-35 and 35-45 indicating a much interest of young professionals on the area of vertical greening.

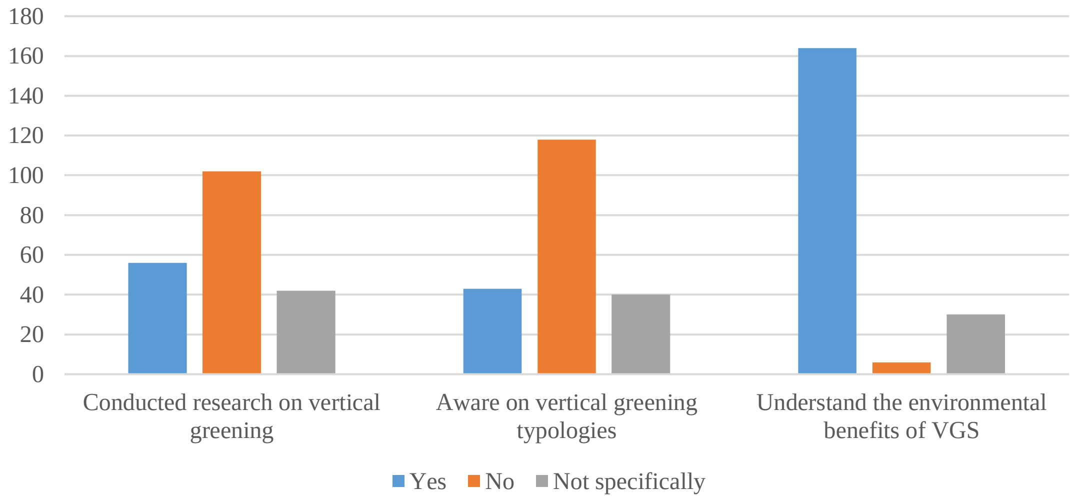
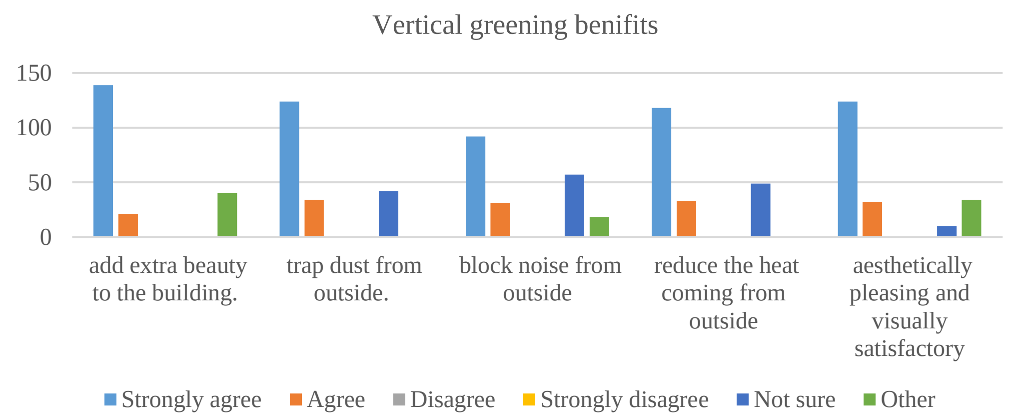


Figure 3.22: Awareness on vertical greenery

Further as depicted in the Figure 3.22, awareness of vertical greening types too showed a similar result indicating unawareness of the majority of vertical greening typologies and systems while a majority confirmed the understanding on environmental benefits of vertical greening.

Aesthetical value of green walls, temperature regulation, air quality control and noise level control, restoration of greenery in urban context, increase of biodiversity, cooling potential were stated as the benefits of integrating VGS in built context. Based on the theoretical knowledge, practical experience and gathered information the participants had rated the benefits of vertical greening where a significant majority had strongly agreed with the stated benefits as shown in Figure 3.23. However, a minority had justified other reasons stating vertical greenery may not always enhance aesthetic beauty of every design concept. On the other hand, a significant majority has agreed on the positive enhancement of physical and psychological comfort with the integration of vertical greening to building facades.



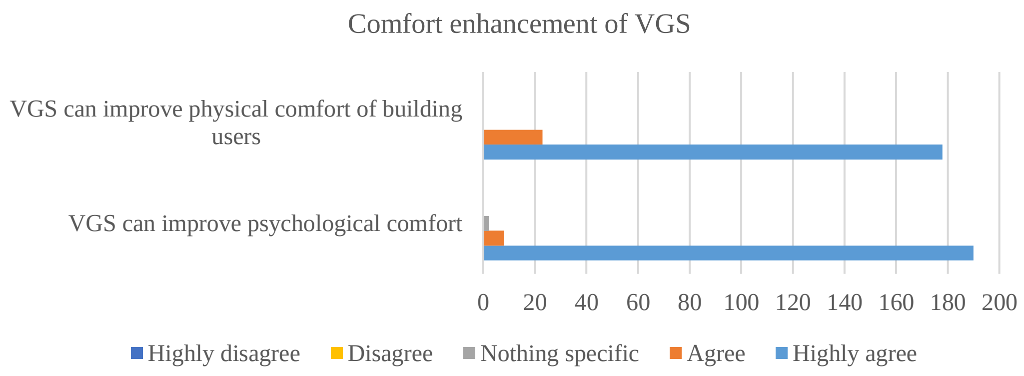


Figure 3.23: Opinion on vertical greening benefits

Difficulty in maintaining the VGS as well as the plant health, damages caused to walls by VGS due to dampness and roots, difficulty in pest controlling were stated as the issues related with vertical greening as shown in Figure 3.24. Difficulty in maintaining the plants and plant health and the high initial costs were the major issues as identified by the majority 23% and 21.5% respectively. Overall it is clear that maintenance related issues are the main drawbacks in vertical greening in terms of building maintenance as well as vertical greenery maintenance.

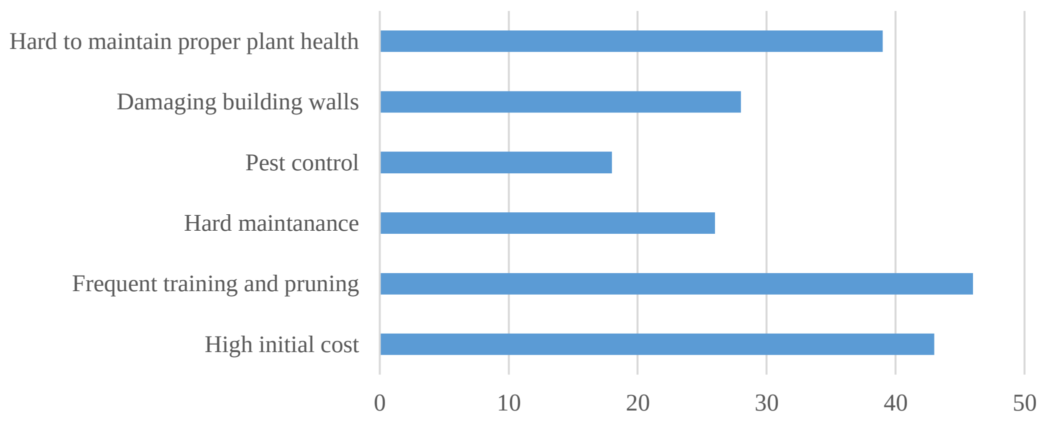


Figure 3.24: Issues related to vertical greening

c) Preference for building façade: before and after application of VGS

From the total responses, 148 respondents (74%) have experienced a building appearance before and after vertical greening application. From the experience majority (70%) has given a positive respond on integrated VGS based on the value addition to the environment (Figure 3.25). However, several arguments had been brought forward on the change of the appearance commenting that integration of VGS to existing buildings must be done only after a thorough study.

Further it was identified that though the practical application of VGS in actual projects were significantly low in present context, a majority of 60% has referred international and local buildings with VGS integration as examples and influences for design development. Further, from the total responses, 66.7% responses plan on recommending vertical greening integration to building designs.

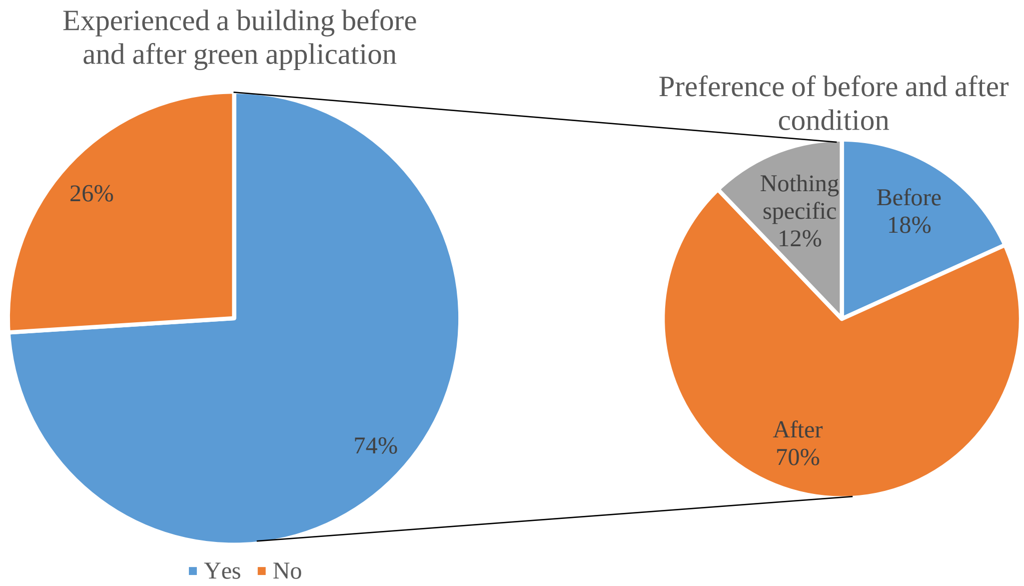


Figure 3.25: Preference on before and after VGS integration

d) Client awareness and demand

In terms of client awareness on sustainable design concepts and their demand on such interventions especially vertical greening is significantly less as per the survey analysis. As per the Figure 3.26, 61% representing the majority has stated that the clients have not requested any sustainable design interventions to their projects and only clients of 9% respondents have specifically asked for vertical greening. It must be highlighted that according to the statements of the participants from the clients that have asked for vertical greening majority have been for commercial level projects requested either to achieve client attraction or to obtain a higher green rating for the building project.

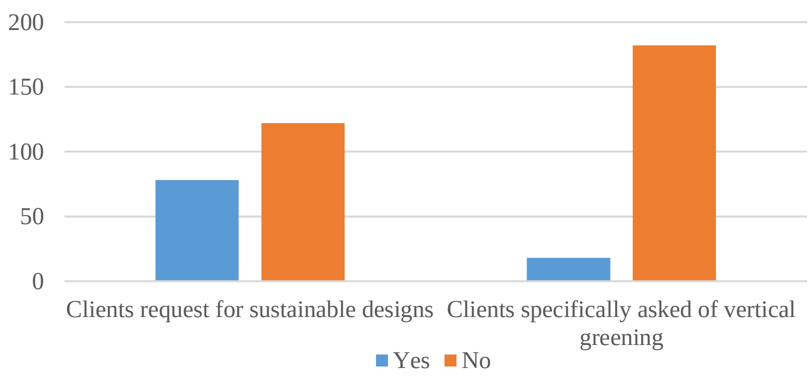


Figure 3.26: Client demand for vertical greening

3.6 Discussion

With the popularization and attention given to vertical greening as a sustainable building integration, people around the world have started adopting vertical greening concepts. Studies related to perception on greenery in neighborhoods have been previously conducted in different contexts. A study has been conducted in Sapporo, Japan on the residents' preference on flower beds along the streets whereas in Singapore another perception study has been conducted to evaluate the expectations and perceptions of residents on roof tops gardens (Yuen & Hien, 2005). Lee et al., (2009) has examined how pedestrian perceive greenery as a design element in sidewalk landscaping in respect to green ratio, tree height and width and shrub width in Korean context.

3.6.1 Public perception on vertical greening

The surveys which were conducted to evaluate the perception on vertical greening in local context too resulted similar outcomes where urban greenery and integration of vertical greenery is perceived positively by a majority. The first questionnaire was conducted focusing on general public. When analyzing the results, it was revealed that with the rising number of buildings in local urban contexts which are being transformed to concrete jungles, attention given on greening the surrounding is taken positively and well accepted by a majority. According to White and Gatersleben, (2011) greeneries on building has a direct influence on the perception of beauty. Mental and physical comfortability gained by integrating vertical greenery along with the aesthetical appeal has been similarly identified by the public in local context as well.

Similar to the results obtained in local context where majority appreciated vertical greening integrated and preferred to have vertical greenery in their own residencies, studies done in global context too has proven the high preference of public on building integrated vegetation in residences due to the aesthetic appeal rather than houses with no green integration. Health benefits such as therapeutic effect, reduction of stress levels and economic benefits such as increment of property value (Wong et al., 2010b) by vertical greenery too have been highlighted by perception studies. High preference for green sceneries obtained by green facades and green roofs over pure building line in urban context too has been highlighted (White & Gastersleben, 2011). As Wong et al., (2010b) states such perception studies also have revealed the stress releasing potential of greenery in hectic urban lifestyles.

Less knowledge on technical aspects related to vertical greening systems and the lack of awareness on building and urban related benefits influenced by vertical greenery is highlighted by the survey responses. This has been a similar outcome in surveys done in international context as well where other than the construction costs, lack of technical knowledge and details on suitable plants in local condition were identified as reasons that impedes VGS integration (Wong et al., 2010b). Cost of initiation, maintenance and issues directly related to these two aspects were mainly indicated as issues that impeded the integration of vertical greenery in local context despite the high likeliness the public had to adopt VGS to their own residences.

3.6.2 Occupant perception on vertical greening

Similar to the responses given by the public, occupants of buildings that were integrated vertical greenery too had given positive response towards green integration highlighting the effectiveness of having greenery in proximity to workplaces. As Gossauer and Wagner (2008) states, aspects related to satisfaction of occupants and thermal comfort are of equal importance when considering energy efficiency of building design and operation. To enhance the productivity and satisfaction of occupants' thermal comfort and quality of air become vital of importance. Natural ventilation, indoor air temperature control, workspace design, thermal sensation and etc. highly influence the thermal satisfaction of the building occupants. Thermal comfort, visual comfort and psychological comfort occupants gain during the work hours due to vertical greenery is depicted through the responses of the majority. This implies the occupants are more satisfied in their work place and work more productively.

Past studies have revealed that workspace atmosphere directly influence the productivity of workers. As per the results, more than 90% of the occupants have highlighted quality of the working environment enhance the mood and attitude on their work whereas 89% highlights the importance of the quality of the working environment in enhancing the sense of their job satisfaction (Samaranayake and Silva, 2010). Type of vegetation, color and shape, density, size and configuration of the plants, seasonality and abundance as well as the location influence the occupants' perception on the urban green infrastructure. Wong et al., (2010b) clearly discuss the peoples' perception and concerns such as technical, cost, knowledge and awareness, supports and barriers on application of vertical greenery systems in practical situations. Expanding the area of green façade, proper maintenance, effective pest control, use of flowering/fruity plants and more cooling plants are suggested by the occupants for the expansion of the green walls in future applications.

Visual enhancement gained by VGS was the main factor identified by many of the occupants despite the many other benefits they offer. Nevertheless, the comfort enhanced by the vertical greenery in terms of mental and physical aspects were graphed to a considerable extent. As per the survey results, more than 50% of the respondents were either highly satisfied or satisfied with the comfort obtained by vertical greenery. However, occupants may not have identified the noise reduction potential of vertical greenery systems due to higher outdoor noise levels in the Colombo area. Similarly, a study carried out in Mandeville city of New Orleans discovered that attitudes of the residents toward the urban greenery especially aesthetic value and shading as the most important facts midst other factors (Jim & Chen, 2006).

Dense foliage and large extent of green walls are capable of influencing a considerable temperature reduction which influence thermal comfort near the green walls. The direct sunlight falling on the green wall is partly absorbed by the plants and substrate while part of sunlight is transmitted (Charoenkit & Yiemwattana, 2016). Hence, reflective heat gain is reduced by the green walls and temperature fluctuation in the microclimate is regulated which influence the thermal comfort near the green walls. Consequently, heat transmission to building interior is too reduced by the heat absorption by plants and substrate, while reducing the scattering and the reflection of incident sunlight. Research findings of Jim & Chen, (2006) signified a substantial high population satisfaction on the shading and temperature reduction by vertical greenery systems in tropics. On the other hand, void spaces in the green walls especially in green façade allow the penetration of sunlight to the interiors and ensure sufficient light level in the working environment.

3.6.3 Designer perception

With the attention given to sustainability of buildings, energy efficiency and their eco-friendliness, professionals around the world are taking different measures to address these through different interventions. Building envelop related design interventions are a common area in this regard, which has gained the attraction of many building designers. Vertical greening too is being adopted in this context as a sustainable façade design intervention based on the many benefits they offer. However, the low application of vertical greenery observed in the local context depicted a gap in practice of vertical green integration in architectural interventions. In global contexts, architectural input in published research on vertical greening is a proof for the design application of vertical greening.

Interest on integrating vegetation in building design is becoming more widespread whereas more researches are being carried out to assess the positive impacts of VGS. According to Perini (2012), architectural publications on greenery integration has significantly increased in numbers from year 2005-2010. This highlights the higher interest of building designers on vertical greening integrations. This trend has continued till today where number of research papers have been published. However, the lack of such local evidence led to the study of designer perception on vertical greening in local context to identify the potential of vertical greening applications as architectural interventions.

Despite the smaller number of architectural vertical greening applications and very less researches and experiments conducted in the area of vertical greenery in existing situation, the survey indicated a high potential of vertical greenery applications as architectural design interventions in coming years. Majority of the responses as shown in the analysis agreed on the acceptability of vertical greening as a sustainable design solution in local context due to the understanding they had on the achievable benefits. The attention on integrating vertical greenery can be related to the growing need of sustainable building interventions which heightens the efficiency of building and environmental conditions. Further, this also implies the intention of displaying such projects as “green” while enhancing the aesthetic value.

A study by Wong et al., (2010b) brings out similar results which considers the perception of building occupants, architects, developers and government agencies. The increase of visual interest by extra beautification, filtering and trapping of airborne dust particles, temperature reduction and cooling the environment, noise attenuation and acoustic insulation and restoration of biodiversity and increased air quality by vertical greenery systems have been highlighted as the identified benefits of the majority. The same population has declined the enhancement of the building lifespan and rainwater retention by vertical greenery systems as benefits of VGS in urban environment.

As indicated by the results the low demand on sustainable interventions and no demand on applications of vertical greening by clients depicts the unawareness of the public of the sustainable aspects of vertical greening. However, high appreciation received by the clients for the projects which were completed with vertical greening integration showcase the possibility of popularizing such concepts in local context.

3.7 Chapter summery

Vertical greening being identified as a sustainable green intervention is now getting popularized in the world. In such a context importance of promoting the application of vertical greening in tropical Sri Lankan context based on the benefits it offers was identified. The research was initiated with the aim of evaluating the benefits of vertical greening in local context and to develop a vertical greening system that is more beneficial. For that, the possibility of popularizing vertical greening and the willingness of people to adopt such interventions needed to be recognized. With that aim, the questionnaire surveys were conducted with the focus on evaluating the perception of vertical greenery in Sri Lankan context.

Responses gained through the study revealed that vertical greenery can be introduced and popularized in local context as the responses were positive towards vertical greening applications. Lack of research evidence and publications and results of the survey implies the lack of knowledge on vertical greening concept, technical details, benefits in terms of building scale and urban scale not just among the public but also among the professional building designers. This implies experiments and research need to be conducted on vertical greening and awareness must be heightened. Apart from the lack of knowledge, maintenance related issues and cost factor are impeding the adoption of vertical greenery by individuals. This again calls the attention to do experimental studies on how to overcome such maintenance issues or to introduce vertical greenery that require less maintenance and less initial and maintenance costs. Nevertheless, the results of the perception study highlight the fact that vertical greenery can be introduced to local context and the application can be expanded by increasing the awareness on the related benefits and methods to overcome high costs and maintenance.

4. IDENTIFYING THE LOCAL SITUATION OF VERTICAL GREENING IN SRI LANKA

4.1 Introduction to the chapter

With the grown interest towards vertical greening as a sustainable design intervention, different approaches of vertical greening can be seen in cities around the world. Parallel to the trend in the world, vertical greening application in local context too can be seen. However, this trend is still in an initial stage. From literature, categorization of vertical greening and four main types of VGS based on construction were identified. However, less research evidence on vertical greening in local context signified the less studies done on the subject area. Therefore, this section of the study focuses on identifying the vertical greening applications, practices and existing vertical greening types in local context based on field investigations and observations.

4.2 Vertical greening applications in local context

As the first step of the field investigation a physical observation was carried out in the Colombo to investigate the existing VGS types (Figure 4.1). In each of the selected twenty case studies, the person in charge of the VGS was interviewed to collect data on plant type, time period of VGS, purpose of VGS, maintenance and watering system.

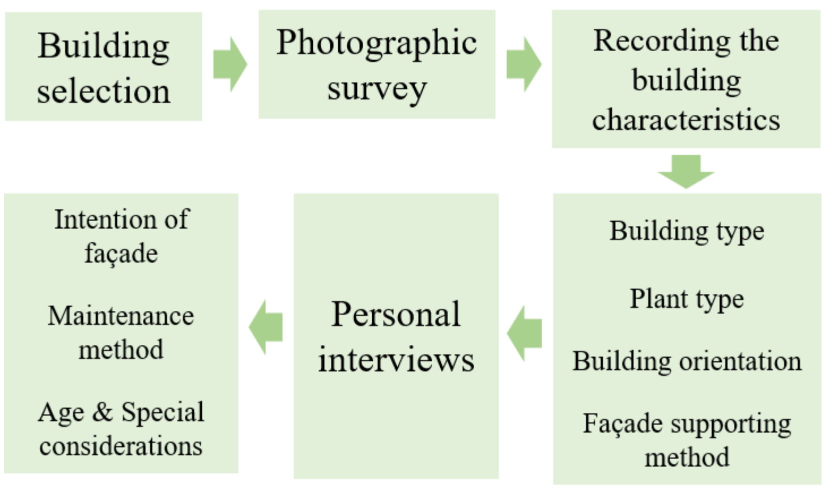


Figure 4.1: Procedure of field study stage 01

As per the VGS types identified through the literature review, the case studies were categorized based on the vertical greening classification: green façade or living wall.

4.2.1 Green facades

From the selected twenty case studies three buildings were identified with direct green facades (Figure 4.2). *Ficus pumila minima* commonly known as creeping fig, climbing fig or money plant and *Thunbergia grandiflora* and *Thunbergia laurifolia* commonly known as Thunbergia are used as plant species for direct greening. Case A was identified as an unintentional direct green façade whereas in case B the intention of the direct green façade has been to cut off direct gain and glare. In case C the boundary wall is intentionally maintained as a green façade yet only with the purpose of aesthetics. Through the case studies it was observed that direct greening for façades is primarily used for boundary walls intentionally or unintentionally in most occasions. Where direct greening was applied intentionally, such walls are covered with greenery only considering the aesthetic appeal.

Figure 4.2: Direct green facades in Colombo context

Seven cases were observed to be indirect green facades supported by either mesh structures, trellis or ropes. Observations indicated that indirect green facades to be a popular vertical greening intervention when considering the vertical greening in Sri Lankan context (Figure 4.3). The interviews conducted with the relevant personals revealed the ease of maintenance and the low cost in installation has attracted the building owners/ designers to use indirect green façade system. Almost all the cases identified as indirect green facades used *Thunbergia grandiflora* and *Thunbergia laurifolia* as the plant species. It was also evident that the trend of indirect green facades is now becoming a popular intervention in many new constructions, mostly in office and commercial buildings.

Case D and F indirect green facades are maintained for 5-6 years, yet with not a specified maintenance system. In case D, plants are incorporated at the bottom and intermediate levels of the green façade. Except in case E main intention of the facades has been to enhance the aesthetic value and trend of green building where less attention has been given for the environmental and sustainable benefits. In case E, creating green facades and green screens has been a main intention since the design concept stage. Thus, choice of plants and façade greening method has been finalized after background research and on-site sampling. Case I and J are purely with the intention of aesthetic appeal whereas in case J indirect green façade is attached to the boundary wall.

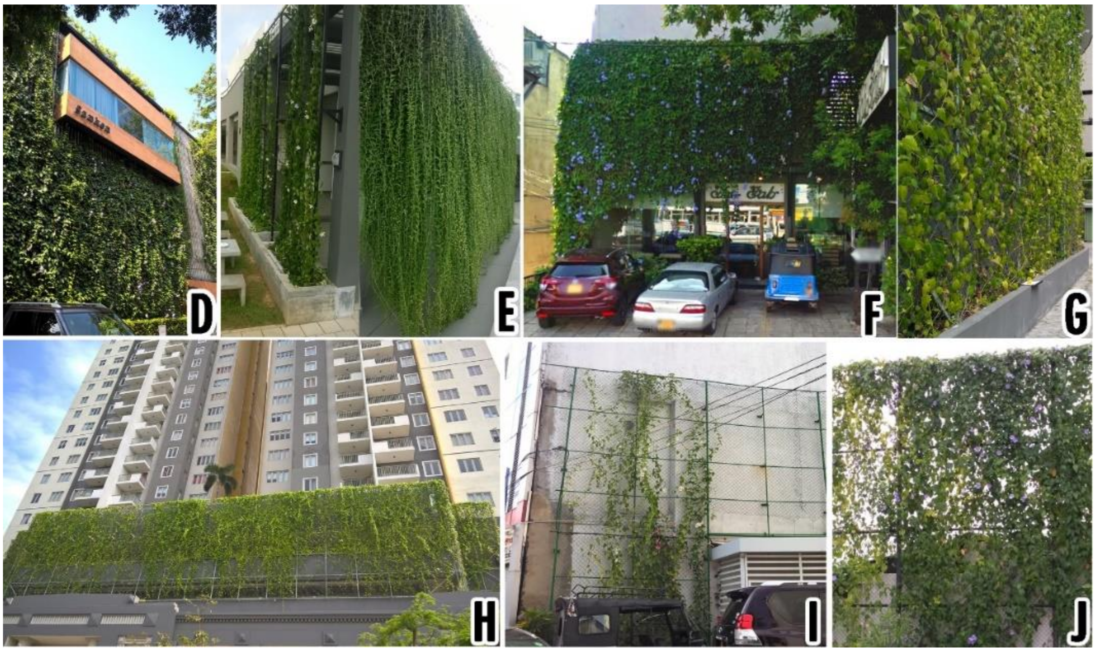


Figure 4.3: Indirect green facades in Colombo context

4.2.2 Living walls

Though many novel and innovative modular living wall systems are available in international context, in present planter box-based living wall systems is the commonly available modular living wall in Sri Lankan context. From the case study it was understood that the trend of integrating living walls is now becoming popularized in Sri Lankan context. Same planter box based LWS is used in all the cases except in case L. In case L, similar methodology to continuous living wall has been adopted, yet in a very simple means (Figure 4.4). Based on the market trend several companies expertise in the felid of implementing living walls are importing the planter boxes and the technology and undertake to implement and maintain the living walls as per the client requirement.

Figure 4.4: Living walls in Colombo context

Plant species such as *Rhoeo discolor*, *Rhoeo spathacea*, Pothos (Epipremnum sp.), Lipstick plant (*Aeschynanthus radicans*), Sword Fern (*Nephrolepis exaltata*), Rabbit’s foot fern (*Davallia fejeensis*), Purple waffle plants (*Hemigraphis exotica*), Baby's Tear plant (*Soleirolia soleirolii)*, *Calatheas* speceies, *Pilea* species, *Fittonia* species, *Hypoestes* species, Maidenhair fern (*Adiantum*) are commonly used as well as Moss rose (*Portulaca grandiflora*), Japanese roses (Portulaca grandiflora hybrid), *Petunia* species, pothos/devil’s ivy (*Epipremnum aureum)*, Chinese evergreens (*Aglaonema),* spider plant *(Chlorophytum comosum),* viper plant *(Sansevieria trifasciata),* Dumb canes (*Dieffenbachia*) are commonly used in these modular living wall systems.

Details of LWS in local context

Plastic planter boxes fixed to a framework is the LWS found in Sri Lankan context (Figure 4.5). Here the planter boxes are filled with growth medium and selected plants (based on each individual preference) are planted. Irrigation system using tubes are used to supply water to the planter boxes from upper level and the system is designed to create the water flow to the lower levels through planter boxes.

Figure 4.5: Planter boxes commonly used in LWS

When considering the findings of the field study and the interviews it was clear that in most of the cases the reason for using vertical greening has been to achieve aesthetical appearance, either to enhance the building outlook or to cover up a monotonous façade. In green facades Thunbergia grandiflora and Thunbergia laurifolia are used either separately or mixed to add some color with the flowers and to improve aesthetic value. Further the species is identified as easy to maintain which requires very less attention after planting. In each case of green facade, no specific watering system or maintenance system is defined whereas different methods are adopted to provide with such requirements based on prevailing weather conditions and etc. fertilizers are used in some cases to enhance the flowering process.

Mix of evergreen shrubs and ferns are used in LWS along with decorative plants to create colorful facades. In these systems similar watering methods are used with tube systems to circulate water to the planter boxes. In general watering is done twice a day in all the cases and nutrients too are supplied along with water as per the requirement. Only in one case the plant selection, environmental benefits were highly considered and a background research was conducted to identify the best potential plants. In two other cases the developers and the owners have considered the benefits of vertical greening in taking the decision of creating LWS yet has not gone into research level. However, it was clear that aesthetics was given the main concern in almost all cases.

4.3 On-site field investigation for thermal performance analysis

Parallel to the basic field survey it was planned to evaluate the thermal environment of the existing VGS. Three case studies representing each existing VGS types were selected. Temperature variation of facades, RH and CO_2 concentration profiles of selected nine cases were measured. On-site experimental investigation was conducted in two steps as basic façade study and performance evaluation

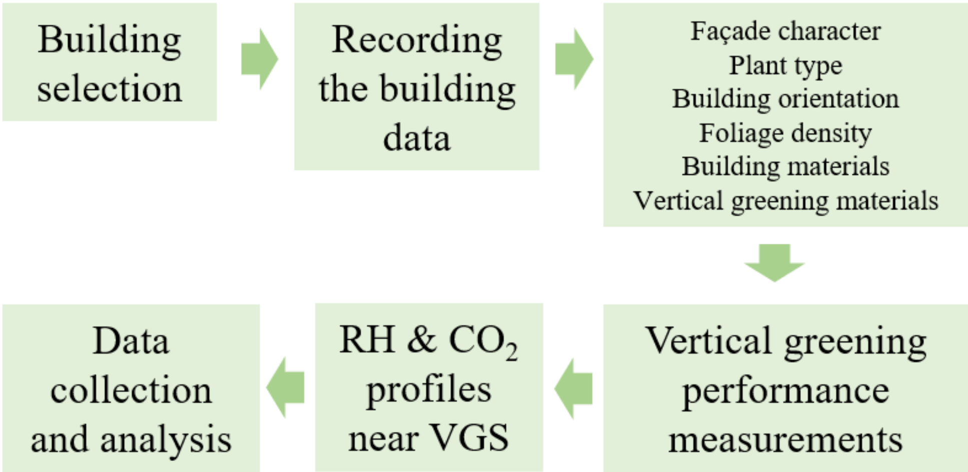


Figure 4.6: Procedure of field investigation for thermal performance analysis

As the first step of the field study for thermal performance analysis basic information related to selected nine cases were collected and recorded on site. Building location, type of building, type of vertical greening and plants incorporated, façade orientation and supporting materials, thickness of the foliage and etc. of each case were recorded. All the selected case studies with vertical greening systems were identified within the Colombo context.

4.3.1 Category 01: Living walls

Table 4.1: Category 01 - Living walls

Case 01;

-Well-established Ferns (*Caledonium*) with high density foliage

-Oriented at East. The living wall was supported with PVC planter boxes and iron mesh.

-Eight months aged living wall

-6 inches foliage thickness

- 5.8 inches air cavity distance between green wall and concrete building wall.

Case 02;

-Well-established *Dracaena reflexa* and, *Ficus pumila* with high density foliage

-Oriented at South.

-The living wall supported with PVC planter boxes and iron mesh.

-One-month aged living wall

-8 inches foliage thickness and 2.1 inches air cavity distance between green wall and plastered cement brick building wall.

Case 03;

Well-established *Crissie birdnest, Fruitz luthi maidenhair, Caledonium,* and Orchids with high density foliage

-Oriented at South.

The living wall supported with PVC planter boxes and iron mesh.

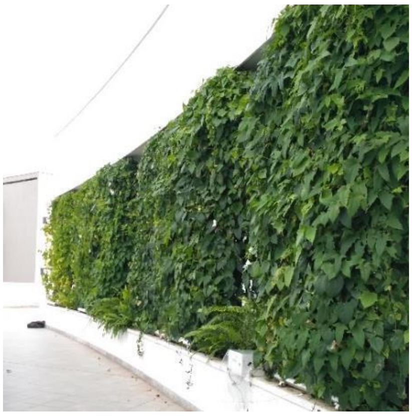
- Six months aged living wall

-10 inches foliage thickness and 12 inches air cavity distance between green wall and plastered cement brick building wall.

4.3.2 Category 02: Indirect green facades

Table 4.2: Category 02 - Indirect green facades

Case 04



-Well-established Blue trumpet vine – *Thunbergia laurifolia* with high density foliage

-Oriented at North East.

-Supported with iron mesh.

-Sixteen months aged green facade

-6.8 inches foliage thickness and 53inches air cavity distance between green wall and plastered cement brick building wall.

Case 05

-Well-established Blue trumpet vine – *Thunbergia laurifolia* with high density foliage

-Oriented at East.

- Supported with iron mesh.

-Sixteen months aged green facade

-9 inches foliage thickness and 53 inches air cavity distance between green wall and plastered cement brick building wall.

Case 06

-Well-established Blue trumpet vine – *Thunbergia laurifolia* with high density foliage

-Oriented at North.

-Supported with coir fiber ropes.

-Sixty months aged

-5 inches foliage thickness and 12 inches air cavity distance between green wall and plastered cement brick building wall.

4.3.3 Category 03: Direct green facades

Table 4.3: Category 03 - Direct green facades

Case 07

-Well-established Ficus species – *Ficus pumila* with medium density foliage.

-Oriented at West.

-Directly attached with the plastered cement brick building wall surface.

-More than 10 years aged

-2 inches foliage thickness and no air cavity between green wall and building.

Case 08

-Well-established Ficus species – *Ficus pumila* with medium density foliage

-Oriented at South East. The direct green facade

-Directly attached with the plastered cement brick building wall surface.

-More than 20 years aged

-3 inches foliage thickness and no air cavity between green wall and building.

Case 09

-Well-established Ficus species – *Ficus pumila* with medium density foliage.

-Oriented at West.

-Directly attached with the plastered cement brick building wall surface.

-More than 10 years aged green facade

-3 inches foliage thickness and no air cavity between green wall and building.

4.4 Performance evaluation of existing vertical greening

Once identifying the basic characteristics, environmental performance evaluation of the selected nine cases was carried out to identify the benefits in local tropical context.

4.4.1 Temperature measurements

Based on previous studies related to thermal performance analysis of vertical greening (Perini et al., 2011a) temperature measurement taking procedure was planned. Graphtec-midi GL820 data logger was used to measure the temperature of selected measuring points. The measurements were obtained on fairly sunny days in months of September and October months. Measurement were taken in real time with a ± 0.002% clock accuracy and 23ºC ± 5ºC of measurement accuracy. Temperature measurements of the vertical greenery and adjacent bare wall were taken to compare the temperature reduction obtained from vertical greenery (Figure 4.7).

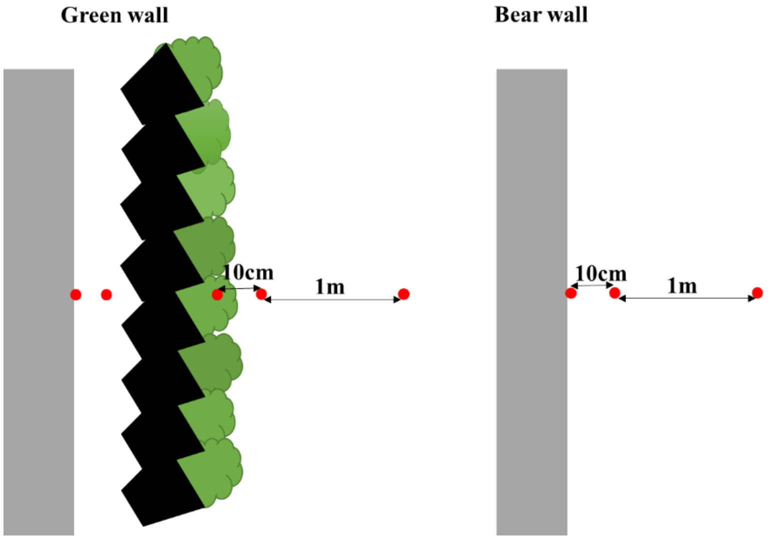


Figure 4.7: Temperature measuring points

The following measurements were recorded:

- Surface temperature of the outer wall shaded by vertical greening and the bare wall
- Temperature of the air gap (when applicable)
- Temperature of the foliage
- Temperature 10cm in front of vertical greening and bare wall
- Temperature 1m in front of vertical greening and bare wall

4.4.2 Relative humidity and CO_2 measurements

Measurements of relative humidity and CO_2 were recorded for two days from 0800h-1700h using the temperature/RH/CO_2 data logger parallel to temperature data. Measurements were taken with 15-minute intervals for each case in comparison to the adjacent bare wall with a 10cm gap from the vertical greening and the bare wall surface. RH measuring fluctuated from 0.1% to 99.9% with a ±3% (10~90%) accuracy level. CO_2 measurements fluctuated from 0 – 9999 ppm with an accuracy level of ± 50ppm ± 5%rdg (0~20000). All the obtained data of temperature, RH and CO_2 were averaged and analyzed.

4.5 Findings of the field study stage for thermal performance analysis

Hourly temperature for the investigated dates were obtained by averaging the recorded temperature measurements for each case. To analyse the data separate graphs were arranged in related to the point of measurement compared to the bear wall measurement.

4.5.1 Living walls

Recorded temperature details which were averaged hourly for living Walls (LW) and adjacent Bare Walls (BW) are presented below. LW1, LW2, LW3 depicts the three cases studies under living walls where BW1, BW2 and BW3 depicts the adjacent bare walls in each case.

a) Temperature at 1m distance

As per the recorded data analysis shown in Figure 4.8 the maximum temperature difference compared to the adjacent bare wall were obtained as 0.31^{o}C, 0.68^{o}C and 0.45^{o}C for LW1, LW2 and LW3 respectively at 1300h. Temperature at 1m distance from vertical green façade and bare wall in each case are almost similar. The data analysis shows no significant difference in temperature at 1m distance from the surface for living walls compared the respective adjacent bare wall.

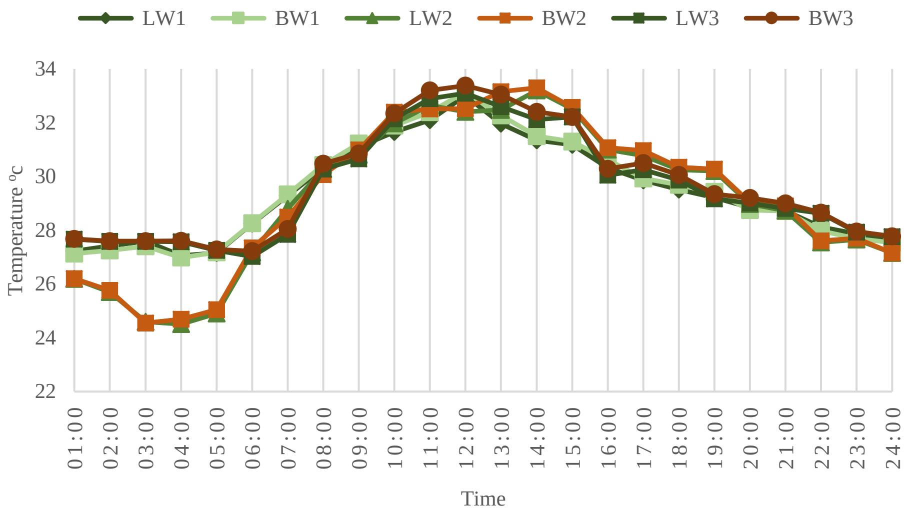


Figure 4.8: Temperature reading of living walls – 1m from the surface

b) Temperature at 10 cm distance

Recorded data signified a maximum surface temperature difference compared to the adjacent bare wall at 1300h as 1.72^{o}C, 1.97^{o}C and 1.32^{o}C for LW1, LW2 and LW3(Figure 4.9).

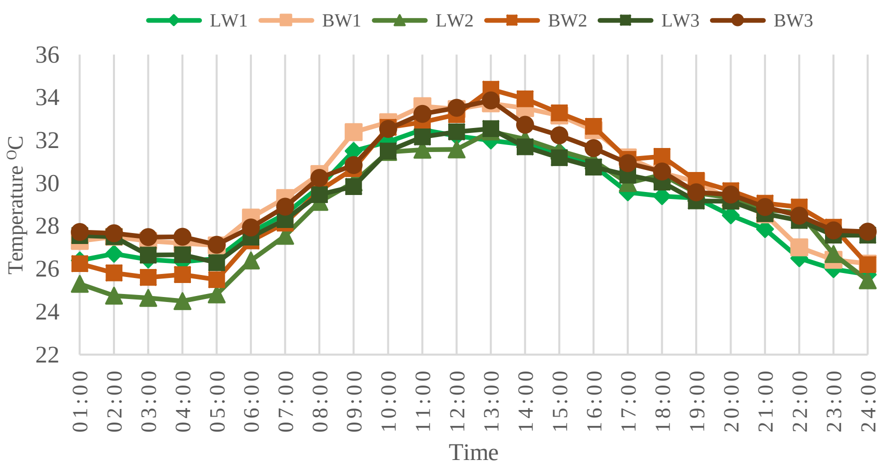


Figure 4.9: Temperature readings of living walls – 10cm from the surface

Compared to the result gained at 1m distance, at 10cm distance from vertical green façade and bare wall showed a temperature reduction in each case. This can be due to the evaporative cooling capacity of greenery.

c) Outer wall surface temperature

Contrasting to the results obtained for 1m and 10cm distance, outer wall surface temperature recording of all three cases displayed a significant temperature reduction compared to the respective bare wall surface temperature during the day time and peak temperature hours. As presented in Figure 4.10 all three walls shaded by the living walls recorded a lower surface temperature recording maximum temperature reduction for LW1 as 10.15°C at 1300h and 9.98°C and 8.57°C for LW2 and LW3 at 1400h.

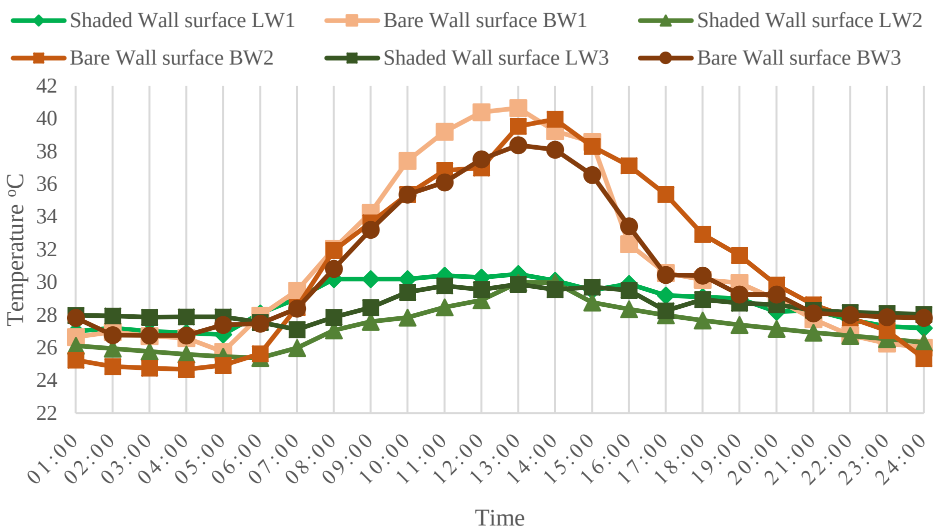


Figure 4.10: Temperature readings of living walls– Outer wall surface

4.5.2 Direct green facades

Below presented are the recorded temperature details which were averaged hourly for Direct Green Facades (DGF) and adjacent bare walls. DGF1, DGF2, DGF3 depicts the three cases studies under direct green facades where BW1, BW2 and BW3 depicts the adjacent bare walls in each case.

a) Temperature at 1m distance

As shown in Figure 4.11 the result obtained at 1m distance from three living wall cases, the temperature readings at 1m distance from direct green facades closely followed the readings obtained at 1m distance from the respective adjacent bare walls of each case. The maximum temperature difference compared to the adjacent bare wall were obtained as 0.64°C, 0.62°C and 0.69°C for DGF1, DGF2 and DGF3 respectively at 1300h. No significant difference in temperature at 1m distance from the surface for direct green facade compared the respective adjacent bare wall was recorded throughout the day.

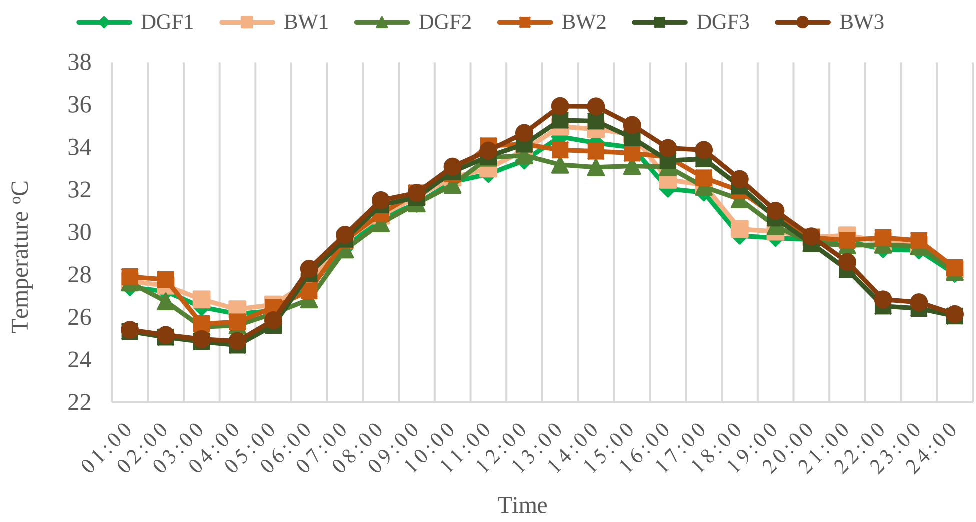


Figure 4.11: Temperature readings of direct green facades– 1m from the surface

b) Temperature at 10 cm distance

During the daytime the temperature difference between the readings at 10cm from the direct green façade and the bare wall showed a considerable difference recording a maximum temperature reduction of 1.62ºC, 1.8ºC and 1.51ºC at 1300h in DGF1m DGF2 and DGF3 in respect to the adjacent bare walls (Figure 4.12). However, the temperature difference is very less during the early morning and late night.

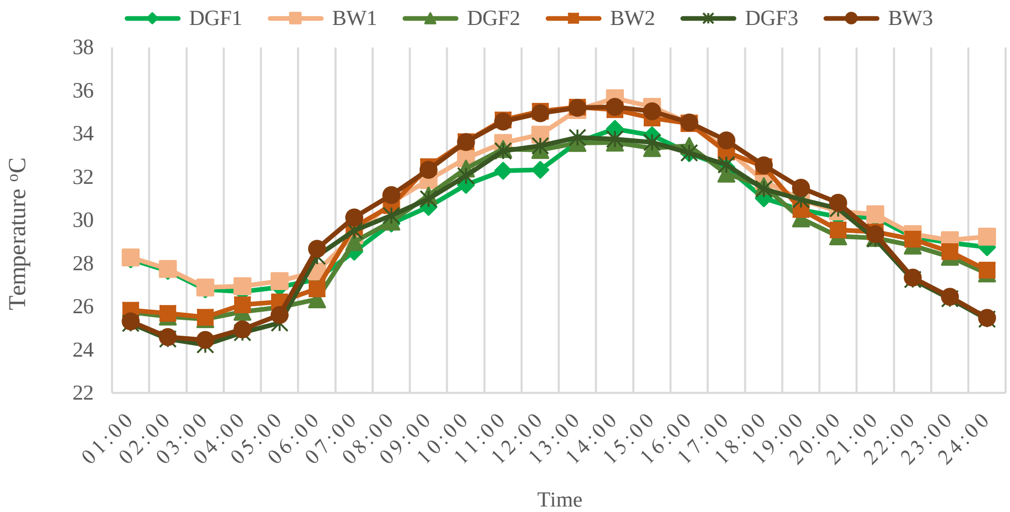


Figure 4.12: Temperature readings of direct green facades– 10cm from surface

c) Outer wall surface temperature

In direct green facades also, the outer wall surface temperature reduction compared to adjacent bare wall outer surface temperature is high during the peak temperature hours. The Figure 4.13 shows the surface temperature readings obtained for each direct green façade case compared to adjacent bare walls. For direct green facades maximum temperature reductions were recorded to be 7.3°C for DGF1 at 1400h and 5.92°C and 7.48°C for DGF2 and DGF3 at 1300h.

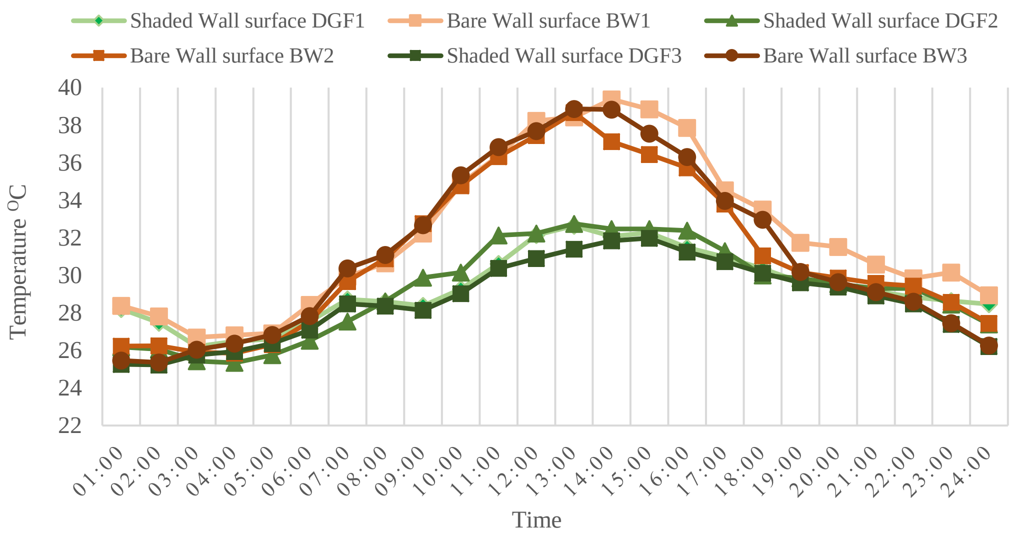


Figure 4.13: Temperature readings of direct green facades– Outer wall surface

4.5.3 Indirect green facades

Similar to previous living walls and direct green facade cases, the recorded temperature details which were averaged hourly in Indirect Green Façade (IGF) cases are presented below. IGF1, IGF2, IGF3 depicts the three cases studies under indirect green facades where BW1, BW2 and BW3 depicts the adjacent bare walls in each case.

a) Temperature at 1m distance

As shown in the Figure 4.14, the recorded data of temperature at 1m distance from the green façade and bare wall surface does not indicate a considerable temperature difference. From the analysis the maximum temperature difference compared to the adjacent bare wall were obtained as 0.61°C for IGF1 at 1300h and 0.70°C and 0.66°C for IGF2 and IGF3 respectively at 1400h.

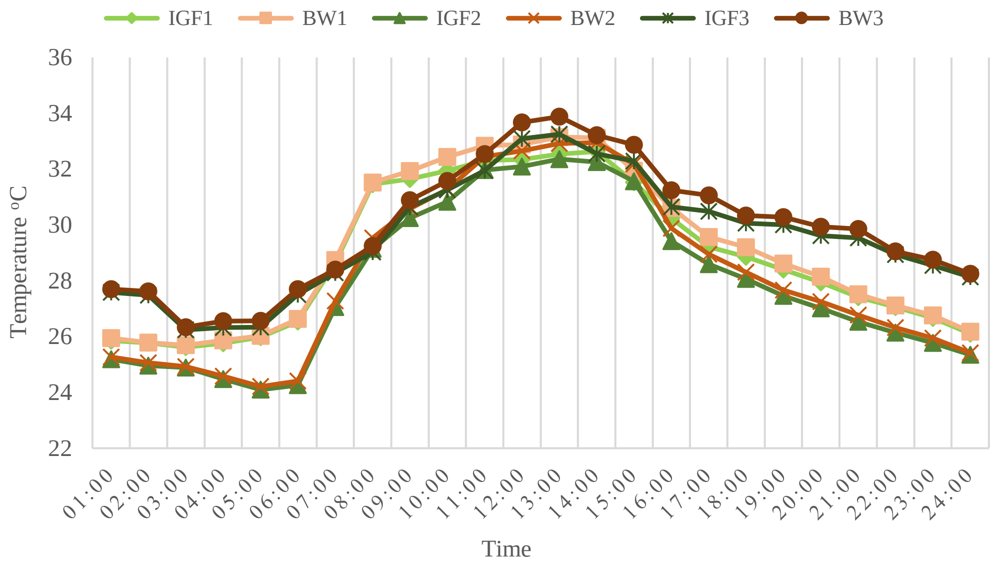


Figure 4.14: Temperature readings of indirect green facades– 1m from the surface

b) Temperature at 10 cm distance

At indirect green facades also during the daytime, the temperature difference between the readings at 10cm recorded a considerable difference with a maximum temperature reduction of 1.65ºC, 1.78ºC at 1300h in IGF1, DGF2 and 1.68ºC at 1400h at DGF3 in respect to the adjacent bare walls (Figure 4.15). The temperature difference here too recorded to be very less during the early morning and late night.

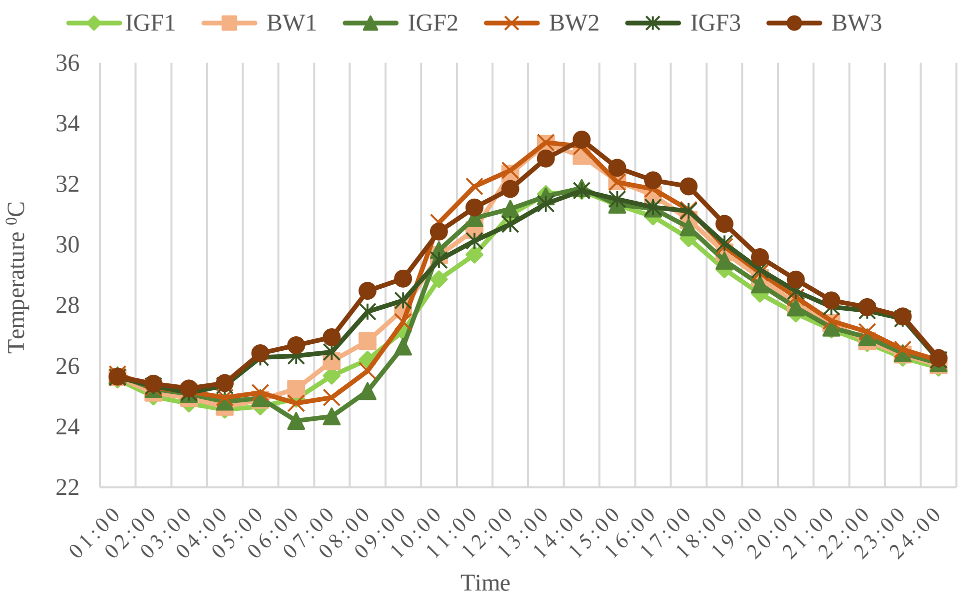


Figure 4.15: Temperature readings of indirect green facades– 10cm from the surface

c) Outer wall surface temperature

Reduction of the outer wall surface temperature compared to adjacent bare wall outer surface temperature at indirect green facade is high during the peak temperature hours. As depicted in the Figure 4.16, the surface temperature readings obtained for each indirect green façade case compared to adjacent bare walls the maximum temperature reductions were recorded as 10.03^{o}C for IGF1 at 1400h and 9.96^{o}C and 7.78^{o}C for IGF2 and IGF3 at 1300h.

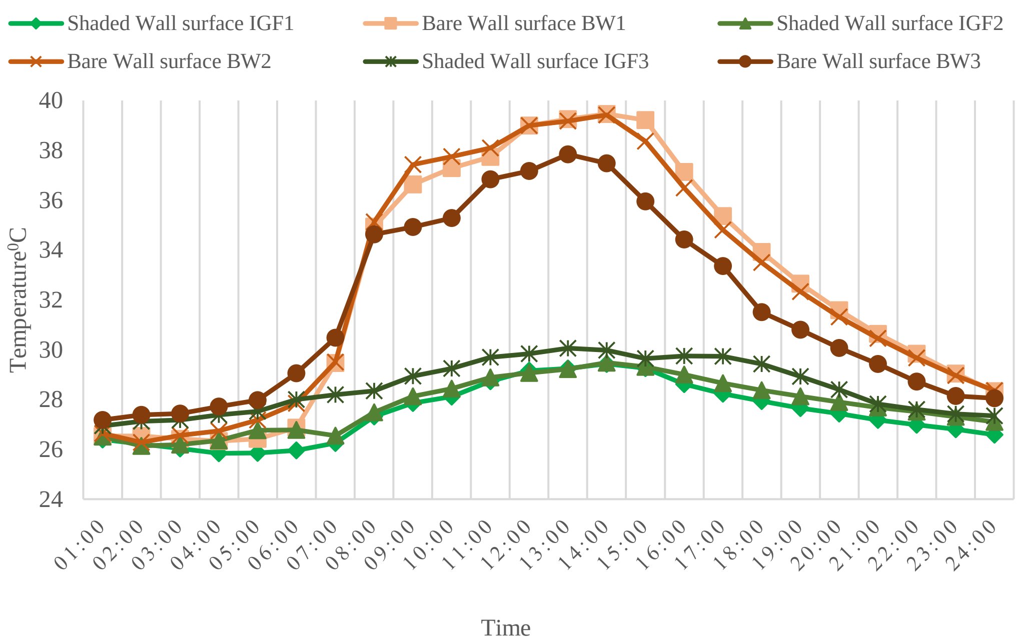


Figure 4.16: Temperature readings of indirect green facades– Outer wall surface

A similar result of insignificant temperature difference between VGS compared to bare walls has been recorded as 0.8^{o}C and 0.7^{o}C in direct and indirect systems at 1m distance in a study done by Peiris et al., (2014). However, as per the findings of Jefas and Silva (2013) temperature difference can be zero in some situations. According to Wong et al., (2010a) at 0.6m distance from the green façade no temperature difference has been identified.

The results of the study conducted in Netherland has showcased a similar reduction of temperature compared to bare wall control at 10cm distance from greened surface as 0.17^{o}C at living walls, 0.13^{o}C at indirect green facades and 0.02^{o}C at direct green facade

(Perini et al.,2011a). Wong et.al., (2010a) reports a 11.58^{o}C reduction of maximum temperature by living walls in Singapore where 5.4^{o}C-5.5^{o}C temperature reduction has been recorded in Netherlands and Mediterranean continent by living walls as per the findings of Perini et al., (2011a) and Perez et al., (2011). Similarly, 9.9^{o}C maximum temperature reduction has been recorded in Thailand (Sunakorn & Yimprayoon, 2011).

The results of a research conducted in Germany demonstrated surface temperature of the shaded wall from VGS as 25.5^{o}C compared to the bare wall surface temperature of 31.0^{o}C in summer condition highlighting the surface temperature regulation potential of vertical greening. A similar result obtained by Wong et al., (2010a) further proves that during the peak temperature hours the surface temperature of exterior facades can be regulated by vertical greening because from 1000h to 1800h time period the surface temperature reduction due to vertical greening is significant.

The findings further suggest that thickness of the foliage, air circulation effect and other external weather conditions as well as the orientation of the façade may influence the effectiveness of the temperature reduction. The effectiveness of shading and the shield of the vertical greenery systems in cutting off the direct solar gain is determined by the characteristics of the VGS and the façade orientation. Hoelscher et al., (2016) too highlight that evapotranspiration of the plants in VGS as well as the shading of the plants influence the cooling and the reduction of temperature.

The air gap between the living wall system and the external wall surface acts as an insulation layer further reducing the heat conduction towards the façade. In direct greening system where there is no air gap the surface temperature is comparatively high further proving the influence of the air gap on surface temperature reduction. However, at night time the surface temperature of the bare walls get cooler compared to the walls shaded by the vertical greening as the bare walls are more exposed to cooler night air. Therefore, the temperature difference at nighttime is much less (Wong et al., 2010a: Hoelscher et al., 2016).

4.6 Relative humidity and CO_2 measurements near existing vertical greenery

Research evidence suggests deviations of RH and CO_2 profiles near vertical green facades due to evapotranspiration and photosynthesis process of plants. To identify the RH and CO_2 behaviour near existing green facades field investigations were conducted.

4.6.1 Relative humidity near the existing VGS

Relative humidity increment influenced by plants takes place in day time when the humidity level in ambient air is least (Sunakorn & Yimprayoon, 2011). The evapotranspiration and the wetness of the substrate in living walls contributes the increment of the relative humidity of the surrounding air. As expected the RH values were comparatively high near the green walls compared to the bare walls. Based on the readings obtained from the field measurements, it was observed that the relative humidity values near all the three vertical greenery types were higher at evening than the noon. At 10cm distance from the green wall surface in all three greenery types an average variation of the RH value compared to the bare walls were observed to be 1.6% - 1.8%. Figure 4.17 shows the RH measurements obtained during 0800h to 1700h at the identified three VGS types. However, based on statistical calculations this variation was identified to be insignificant. As Perez et al., (2014) too highlights the effect of humidity, temperature and the air movement in thermal regulation emphasizing the effect of RH value in regulating the thermal environment near the vertical greening systems specially in the air gap between the exterior wall surface and the vertical greening.

The study by Chen et al., (2013) has recorded a 0.3% high mean relative humidity value at the sealed air gap between the external wall surface and the green façade. Chen et al., (2013) has further stated that even though the microclimatic condition and heat transfer is influenced by the living walls, their capability in increasing the humidity of the air layer compared to the ambient value is much less. A maximum increment of 6.8% in RH value has been recorded which had slightly affected the thermal comfort condition of the occupants (Sunakorn & Yimprayoon, 2011). The study by Sunakorn & Yimprayoon (2011) has further highlighted that at night time the RH value inside a closed room with leaves is less compared to the outdoor RH value.

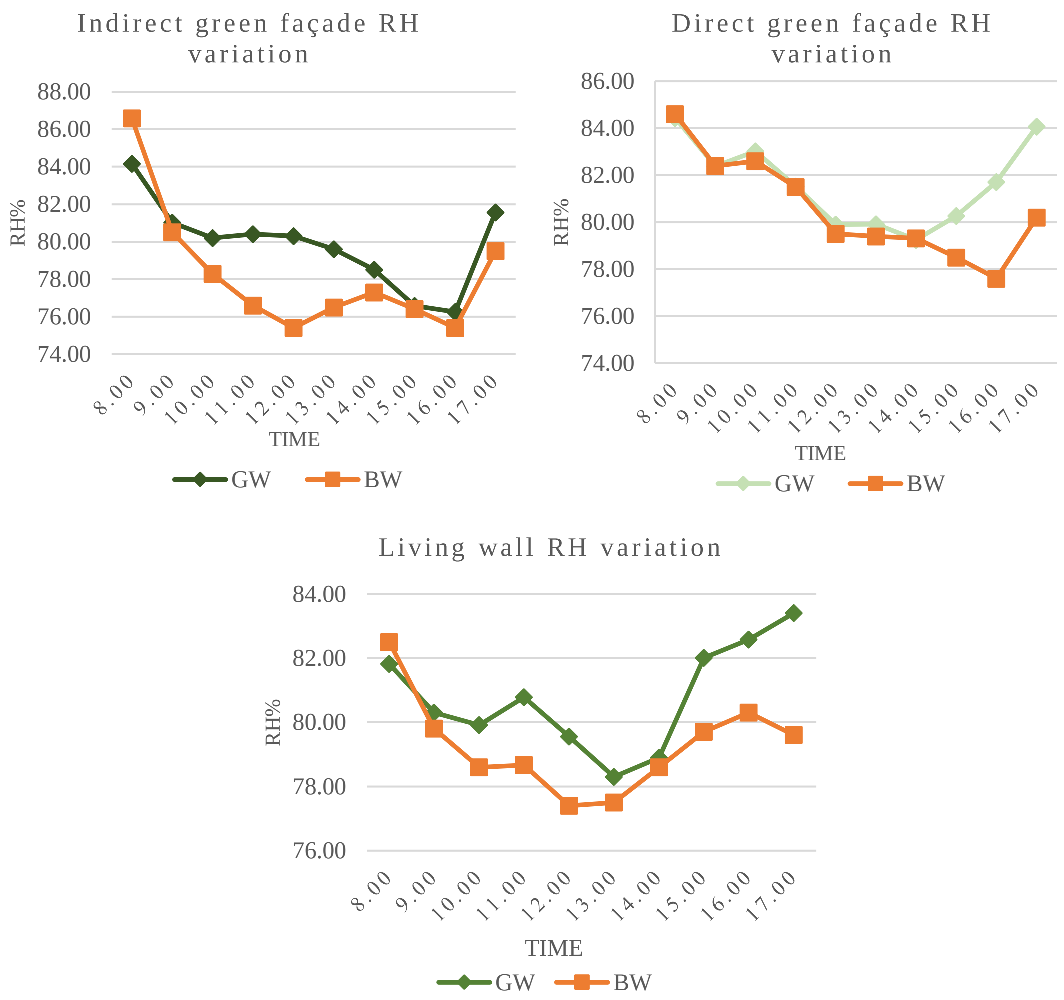


Figure 4.17: RH variation near existing VGS types

4.6.2 CO_2 profiles near the existing VGS

At daytime the recorded average reduction of CO_2 was obtained as 0.63% for living walls and indirect green facades and 0.15% for direct green facades. Further, the readings reveal that the CO_2 concentration has been lower at the living walls and indirect green facades compared to bare wall situation throughout the day where only at direct green façade the CO_2 concentration near greenery has recorded to be high at night time (Figure 4.18). This can be due to the other microclimatic influences and as only point measurements have been recorded.

A study done by Li et al., (2010) records a 2% of CO_2 reduction in green vicinity during day time highlighting that the effect of the photosynthesis process of plants at day time and the high respiration of plants at night time influence this variation in CO_2 concentration around greenery. As stated by Li et al., (2010) plant type, wind condition and solar intensity may influence the reduction of CO_2 concentration. A simulation study conducted by Marchi et al., (2014) has revealed that $98m^2$ area of vertical greenery can capture an average of 13.41 – 97.03 kg CO2eq CO_2 flow annually. This highlights the benefit of vertical greening in regulating the microclimatic conditions. Further such contribution directly helps in mitigating the urban heat island effects in local urbanities.

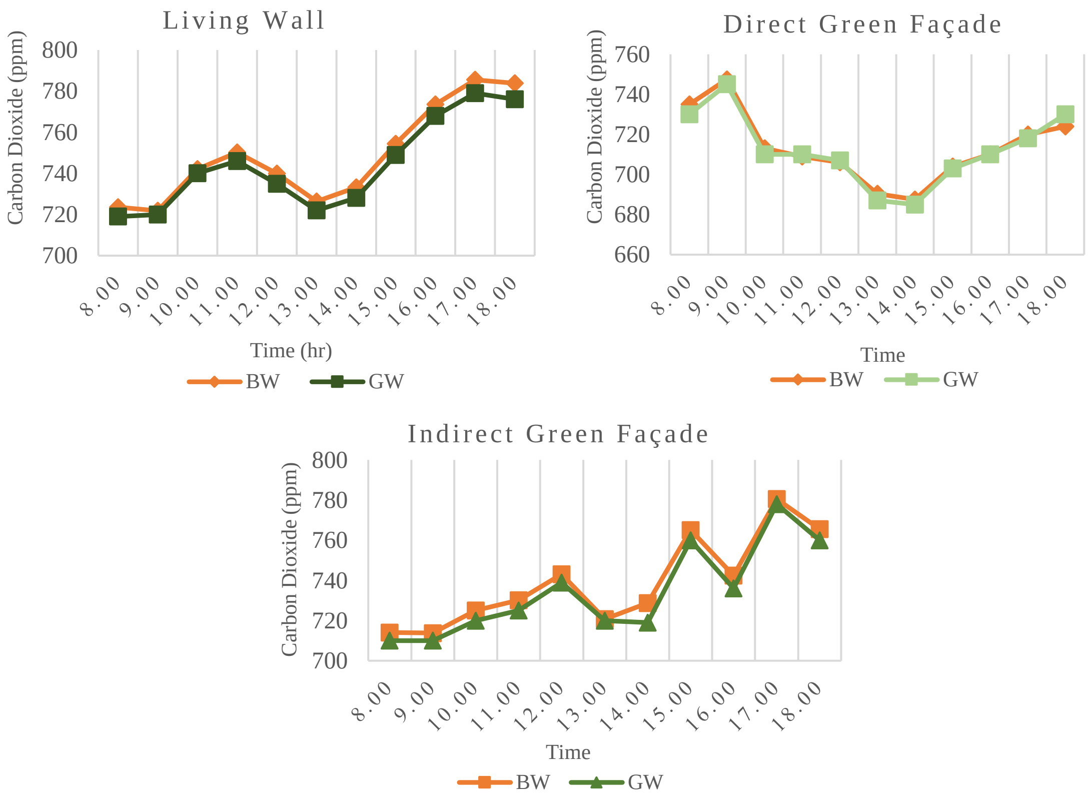


Figure 4.18: Carbon dioxide profiles for green wall types

4.7 Internal air temperature moderation through VGS

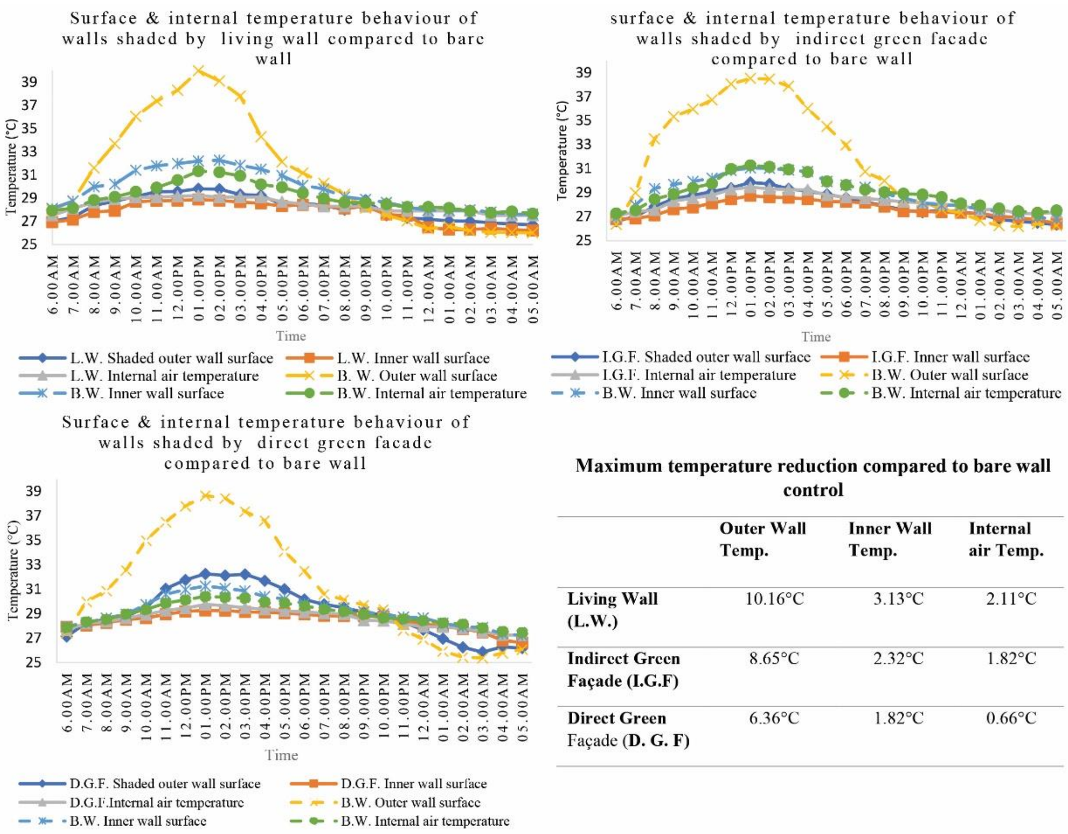
Following the stage one, stage two of the thermal investigation was carried out where one case representing each vertical greening type was selected to study further the temperature reduction gradient from exterior to the building interior (Figure 4.19). Measurements of temperature was taken with a ± 0.002% clock accuracy and measurement accuracy of 23ºC ± 5ºC. Temperature measurements were taken at 2m height from the base level of the green wall on foliage surface, in the air cavity (when applicable) and on the wall surface shaded from each vertical greening type and internal wall surface directly behind the shaded wall. Further the internal temperature of the built space in all cases too was measured. Same measurements were taken on an adjacent bare wall surface exposed to same climatic conditions, on the internal surface of the bare wall and also the internal temperature of the space with the bare wall. Each type was measured for 48 hours in real time to obtain temperature measurements using Graphtec- midi GL820 data logger with 10min interval.

Figure 4.19: Selected case studies for further on-site investigation (A- Living wall, B- Direct green façade, C- Indirect green façade)

Temperature data were measured for 48 hours using Graphtec midi GL820 datalogger following the same procedure and measurement points mentioned at the stage one thermal performance analysis of the existing vertical greening systems; on the wall surface shaded from each modular panel type, internal wall surface directly behind and the internal air temperature. Same measurements were taken on the adjacent bare wall surface and the internal surface of the bare wall.

Findings of the field study for internal air temperature moderation through VGS

Similar to the results obtained at stage one as well as the reviewed literature the temperature difference of the shaded wall outside and inside compared to the bare wall control was considerably high recording a maximum temperature difference of 10.16°C, 8.65°C and 6.36°C in external side of the walls whereas 3.31°C, 2.32°C and 1.82°C (Figure 4.20) temperature difference in internal side of the walls in living wall type, indirect green façade and direct green façade respectively compared to their adjacent bare walls indicating a reduction of external thermal gain through the building façade. Further the internal temperature measurements of the buildings incorporated with all three VGS types were less than the buildings with bare wall façade at each situation recording a maximum temperature difference of 2.21^{o}C, 1.82^{o}C and 0.66^{o}C temperature difference compared to each bare wall situation in building interiors of living wall type, indirect green façade and direct green façade accordingly as shown in Figure 4.20.



Maximum temperature reduction compared to bare wall control

	Outer Wall Temp.	Inner Wall Temp.	Internal air Temp.
Living Wall (L.W.)	10.16°C	3.13°C	2.11°C
Indirect Green Façade (I.G.F)	8.65°C	2.32°C	1.82°C
Direct Green Façade (D. G. F)	6.36°C	1.82°C	0.66°C

Figure 4.20: Results of the thermal performance on-site investigation of the existing vertical greening systems

4.8 Chapter summery

The chapter focused on identifying the existing situation of vertical greening in local context, existing types and their performance. Three vertical greening types namely living walls, direct green facades and indirect green facades were identified in the local context where indirect green facades were more popular due to easy installation and maintenance. The results from the analysis of VGS in existing condition signified that all three existing vertical greening types are beneficial in reducing the surface temperature of buildings where living walls recorded the highest temperature reduction of 10.15^{o}C at the façade shaded by the living wall. Maximum of 7.48^{o}C and 10.03^{o}C surface temperature reductions were recorded from direct green facades and indirect green facades respectively. Internal air temperature reduction was recorded to be 2.21^{o}C, 1.82^{o}C and 0.66^{o}C by living wall, indirect green façade and direct green façade. Average relative humidity increment by 1.6% - 1.8% and an average CO_2 reduction by 0.63% were recorded at vertical greening systems compared to bare wall control. The surface temperature reduction compared to the bare wall control which were recorded to be significant in all three vertical greening types highlights the potential temperature reduction to building interiors.

Findings of the international research too highlights that vertical greenery systems can be beneficial in thermal regulation in outdoors up to 10cm from the façade surface. And the evidence suggests the temperature variations recorded at 1m and 10cm were not significant comparatively. However, since the studies have quantified the temperature variance based on point measurements, in a macro scale the effect of vertical greening on thermal regulation may have a further effectiveness or vice-versa.

Different layers in a living wall system such as the substrate, plants, growth medium, supportive structure, plant container etc. contribute in direct solar gain cut off resulting a higher surface temperature reduction. Therefore, the effectiveness of living walls in terms of thermal regulation is much higher than the other VGS types. This was evident from the field investigation results as well. Thus, in developing a vertical greening system to obtain the best potential benefits in tropical context living wall is identified as the best VGS type.

5. PLANT SPECIES AND GROWTH MEDIA SELECTION FOR THE PROPOSED MODULAR PANEL VERTICAL GREENING SYSTEM

5.1 Introduction to the chapter

With the findings on the existing VGS it is evident that establishing vertical greenery in local context can be beneficial in terms of external and internal climate modification in tropics. The evidence suggests in obtaining the best thermal benefit living wall type is much beneficial. Therefore, based on the findings the research focus on developing a modular living wall type vertical greening system. when developing a VGS for the tropical context, it is essential to identify a suitable plant species and a growth media that is appropriate for the plant species and for the modular panels as well. This chapter presents the work carried out and the results and evaluation of the field studies conducted on plant selection for the proposed modular green panel and the suitable growth media.

5.2 Selection of the plant species

Due to the numerous ecological benefits such as natural cooling, air purification and etc. use of vegetation in building periphery is becoming a higher consideration in modern building designs to increase the buildings' surrounding quality. Plant selection for vertical greening can enhance the aesthetic aspect of the VGS while also influencing the functionality and the thermal benefits as well. In the early stages living walls have been constructed with epiphytic plants that grow in tropical forests (Koska et al., 2013) which eventually changed to wide plant varieties with adaptability to vertical living. By today the plant collection for vertical greening extends from epiphytes and lithophytes to ferns, succulents, shrubs, herbaceous, climbing plants and etc. (Weerakkody et al., 2017). According to the microclimate and location the plants used for vertical greening may vary. Majority of the plant related studies for vertical greening has been conducted in temperate regions. Therefore, effective reference for plant species to be used in tropical context is very less.

In addressing this gap and to identify the most appropriate plant species for the proposed vertical greening system an experimental study was conducted. The plant selection was conducted as a field study envisaged to identify the potential plant species for the vertical greening system and utilization of selected growth media to assess the cooling effect. To conduct the field study as the first step, shortlisting of potential plant species was conducted based on several factors. Height of the plant is a crucial factor when utilizing for vertical greening and roof terraces to enable them to withstand the high wind velocities. From the findings of the research conducted by Snodgrass & Snodgrass (2006) and Perkins & Joyce (2012) ideal plant height lies between 2.5cm – 15cm. Further Snodgrass and Snodgrass highlights that the rate of plant spread over a period of year should be between 15cm -25 cm. Plants ability to grow in shallow, well-draining soil and even in nutrient poor soil too must be considered (Cameron et al.,2015: Johnston & Johnston, 2004). Plants with shallow and dense root system with stems that can root to the substrate too are attractive choices for vertical greening (Dunnett & Kingsbury, 2008).

With expert advice, available literature and observations on the plant species that were already used in existing local vertical greening systems, twelve plant species were shortlisted for the on-site investigation. As Cameron et al, (2015) states when selecting the plants for a vertical greening system factors such as high winds, shallow soils, drought and intermittent flooding, shortage of tree cover must be considered along with the plants' growth form and the growing medium. Three replicates were created from each plant type of which different plant physiological parameters including leaf area index, average leaf dimensions, plant growth rate, plant height were tested and compared. Sample panels were created, and the saplings of selected plant types were planted and maintained under controlled conditions till the plants achieve their optimum height. Then the panels were tested for their survival ability and etc.

5.2.1 Fabrication of green panels

Based on the findings of existing VGS, modular panel living wall system (which comprises of self-contained units planted ex situ and later assembled and fixed on the wall vertically) was selected as the VGS type for the research. Panels for the plant selection on-site investigation was prepared using timber as the material. The size of an individual panel was decided to be 300mm (width) x 600mm (height) and 40mm total thickness with the growth media layer. To improve the durability by improving the water resistance, two coats of wood care sealer with thinner solvent was applied to the modules. Each panel was separated into two parts horizontally to improve the stability of the panel as well as to hold the growth media once the panels are kept vertically (Figure 5.1). To allow excess water to drain out several holes were made at the bottom of the wooden panels. A west facing wall exposed to direct sunlight was selected to fix the panels for the on-site investigation.

5.2.2 Selection of growth media

Since the panels are to be kept vertically and for easy handling of panels weight of the growth media must be kept at a lower value. Being light weight with a high water retaining capacity and binding ability coir fiber was identified to be ideal as the growth media. Further, the physical structure of the coir fiber media with its ability to maintain the balance between air and water in the medium while being irrigated and afterwards as well, make coir fiber a productive growth medium. Therefore, based on the existing literature and agricultural expert knowledge coir fiber was selected as the main component of the growth media for the vertical greening system. Once finalizing coir fiber as the main growth medium component, 1-inch thick layer of coir fiber was layered in each timber panel. Altogether, thirty-six panels were created to plant the selected twelve plant species in three replicates where each panel was fabricated following the same prototype and only the plant species was changed.

Figure 5.1: Creating the modular panel samples

5.2.3 Irrigation and fertilizer application

Manual irrigation using sprayers was practiced in morning twice a week. Water was applied till the growth medium become wet, but applying too much excess water was avoided in the early stages of the plant saplings. Further, retaining heat and moisture required for the plant growth too was highly considered. For each panel, 0.5L of water was applied through sprayers in the first month and afterwards panels were hand-watered from the top based on the water requirement of the plant to maintain the growth and health.

Selected growth medium lacked the nutrients that needed for the plant growth. Therefore, application of nutrients was required. Since the plants do not require nutrients until the appearance of true leaves, only clean water was applied till then. Once the true leaves started to unfold application of nutrient was started gradually. Albert solution is commonly used as a water-soluble nutrient that is used in drip irrigation and foliar spraying as the chlorine free formula consists of wide range of essential nutrients for plant growth balanced with nitrate nitrogen and instantly dissolves in water. Further the premium and balanced ingredients enriched with basic chelated micronutrients has made the selected nutrient solution ideal for the fertilizer application. 0.5g of Albert's Solution was dissolved in 500ml of water to prepare the nutrient solution which was applied twice a week.

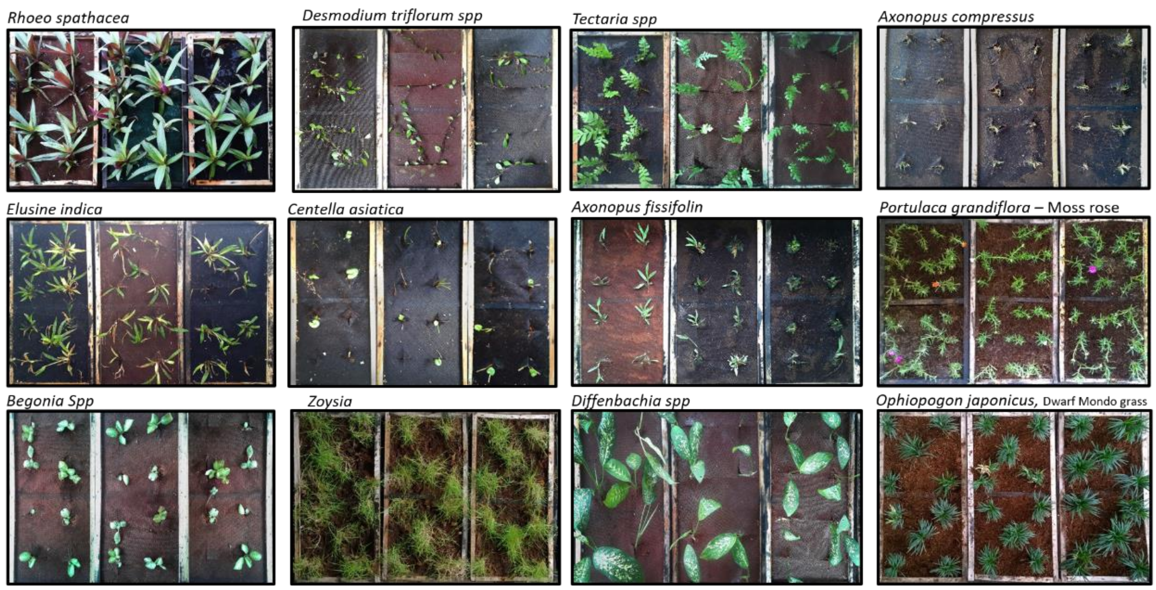


Figure 5.2: Experimented twelve plant species

As stated above the on-site investigation on plant selection was limited to the shortlisted and selected twelve plant species (Figure 5.2). The sample panels were tested under the prevailing climatic condition of the time period the investigation was carried out.

5.3 Plant selection on-site investigation

Completely randomized design method was adopted for the plant selection on-site investigation. Each plant species of the selected twelve plants were replicated in three panels and eight plants of each species were planted on each panel to investigate the growth patterns, survival and heights of the plants. Experiment on plants were conducted for four months where evaluation was conducted monthly. Height of the plants were measured along with the development stages through visual assessment and incidence of pests and diseases. Graph paper method was used in measuring the leaf length and width. A three-point scale was utilized to evaluate the plant health during the time of investigation as 1 = thriving, 2 = alive, but with signs of pest, disease or other stresses, 3 = dead. Mini tab and statistical analysis software packages were utilized to analyze the data obtained through the plant selection experiment. For each evaluation time a separate analysis was conducted. Turkey's studentized range multiple comparison test was conducted to compare when a significant difference was found between two species.

5.3.1 Results of the plant behavior investigation

The result of the plant survival analysis is depicted by the Figure 5.3. During the period of observation, the survival of the twelve-plant species significantly varied among each species. Drought tolerance and long-term coverage (Tan & Sia, 2009: Dunnet & Kingsbury, 2008: Perkins & Joyce, 2012) of plants become vital in selecting a plant species for the vertical greening system. Further ability of regenerating after stress periods (Tan & Sia, 2009), adaptability to local climatic condition and existing environmental conditions (White & Snodgrass, 2003: Chow et al., 2018: Zang et al., 2018) and the plants' resilience in terms of ability to survive in direct sunlight and strong winds, self-sustainability and ability to withstand nutrient deficiencies (Cameron et al., 2015: Son et al., 2014) are essential characteristics the selected plant species. However, the plants that survived had a consistently high health and the only observation was a minor bacteria blight spots during the last month of observation. As resulted, over the trial period vegetal survival rate was highest in *Rhoeo spathacea* species whereas *Axonopus compressus, Ophiopogon japonicas, Portulaca grandiflora*, *Axonopus fissifoliu* and *Elusine indica* too showed a high survival ability. *Zoysia spp* too indicated a high survival and growth rate yet slightly lower than the best survived plant species.

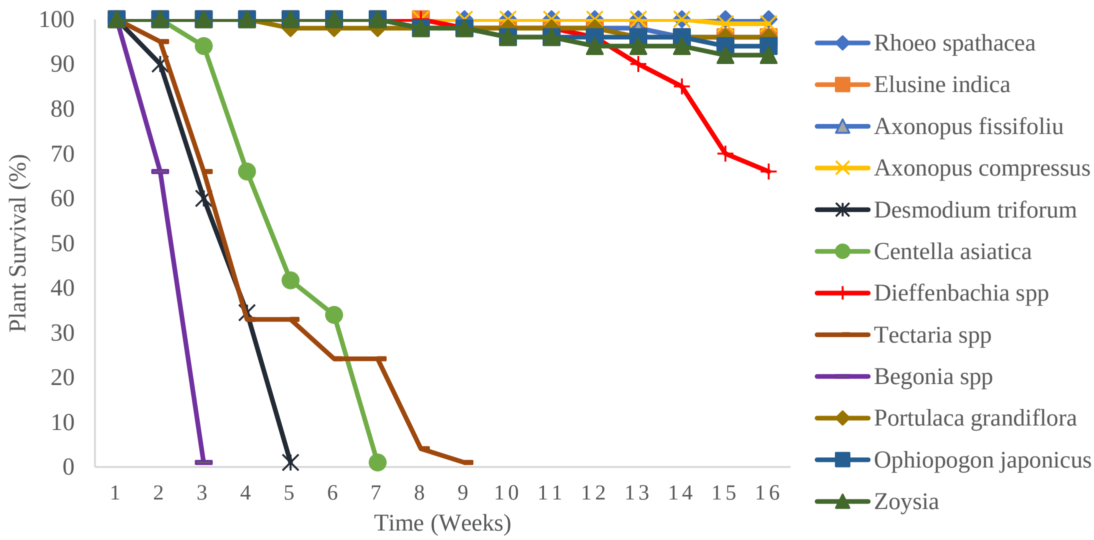


Figure 5.3: Plant survival percentage during the trial period

Growth rate of *Begonia spp* was insignificant and the plant growth started declining from the second week and could not survive after the third week. During the trial period *Desmodium triflorum* and *Centella asiatica* species too displayed a decline in survival from the third week and fourth week respectively and could not survive throughout the period of observation. Through observation it was identified *Tectera* species had a slow pace of growing and the capability of survival was also weak. Survival rate of *Diffenbachia spp* was high in horizontal surface, but the possibility of maintaining the plant in vertical surface was difficult therefore the survival rate too got lower.

Similar to the survival capability, the plant growth rate of the investigated plant species too showed a significant variation during the experimented time period. From the twelve-plant species *Dieffenbachia spp* demonstrated a higher growth in terms of plant height and leaf area index compared to the other plants during the first half of the observation period. After eight weeks, the panels were kept vertically to observe the adaptability in vertical greening. Since the *Dieffenbachia spp* stems which were taller had a tendency of downward growing across the vertical panel it restricted the outer growth reducing the plants' compatibility as a plant suitable for vertical greening. Further the high growth rate and the size of the plants too signified an unsuitability for vertical greening. As Perkins & Joyce (2012) too highlights, similar circumstance in vertical greening plants can cause mechanical unsettling of the vertical greening system influencing the issues related to survival in high wind velocities as well as maintenance and human handling. *Tectaria spp* which displayed a similar rapid growth in terms of plant height too was indicated to be unsuitable for vertical greening system with a less thickness in the modular panels.

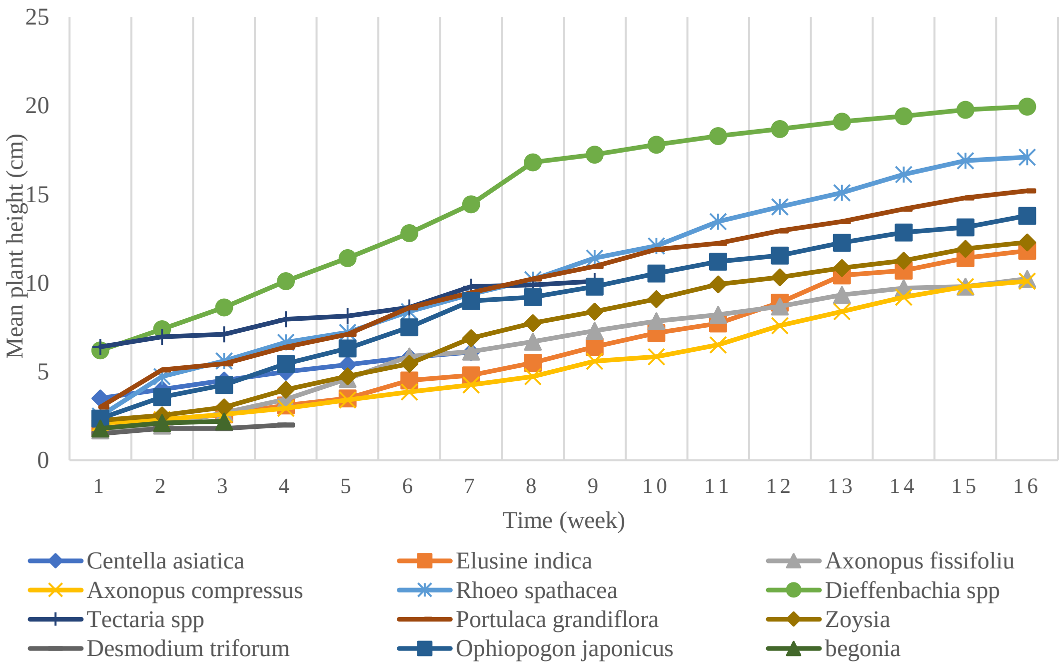


Figure 5.4: Plant height increment over the observed time period

Canopy structure of the plant including the horizontal leaf distribution, foliage density, dense clumping or forming of mat, different coloured vegetation (Wong et al., 2010: Barrio, 1998) is vital in selecting the plant for the vertical greening system. Compared to the investigated twelve plants *Rhoeo spathacea* signified the best outer growth and highest rate of spread over the panel surface during the experimented time period. Further, the high canopy density of the vegetated foliage of *Rhoeo spathacea* was identified as a positive fact in making the plant species an attractive choice for a vertical greening system (Badrulzaman et al., 2015). *Axonopus compressus* too was observed with dense foliage and high rate of spreading with time. Other plant species which were observed to be high in survival such as *Ophiopogon japonicus, Portulaca grandiflora*, *Zoysia*, *Elusine indica* reached 10-15cm in height even though the spread of the plant over the vertical surface was slower in *Portulaca grandiflora* species. According to Snodgrass & Snodgrass (2006), this height range is ideal for vertical greening due to the less tendency in wind damage and capability in easy maintenance.

Based on the growth performance and the survival capability of the shortlisted twelve plant species, five plant species were selected for further on-site investigations. Selected plant species were *Rhoeo spathacea, Axonopus compressus, Portulaca grandiflora, Ophiopogon japonicas and Elusine indica*. Five replicates of each selected five plant species were created and kept under exposed conditions for a period of two months in vertical plane. After the period of observation initial thermal performance measurement was conducted.

5.3.2 Results of the pilot observation of sample panel thermal behaviour

On a selected day with a clear sky the temperature data for 24 hours were recorded accordingly. Temperature measurements; substrate surface temperature, temperature behind the panel and ambient temperature 20cm in front of the canopy surface were recorded using a data logger GL 820 midi.

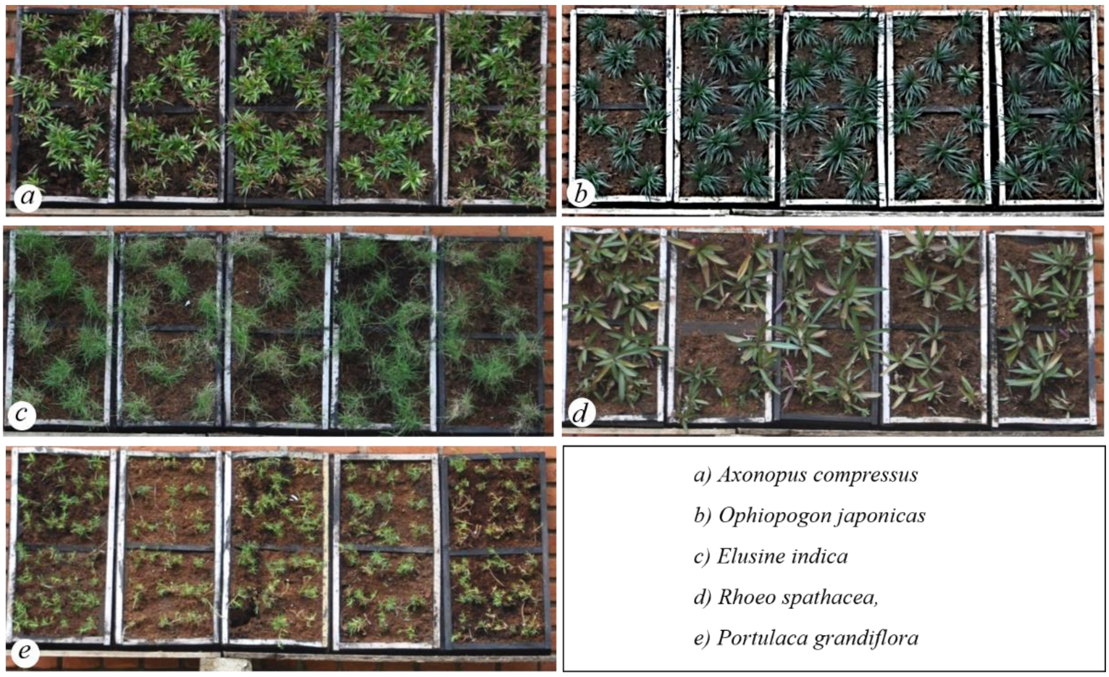


Figure 5.5: Selected five plant species for thermal behaviour observation

a) Temperature at 20 cm distance

Air temperature measurements at 20cm in front of the panels closely followed each other recording no significant temperature difference throughout the study period. Figure 5.6 depicts the temperature measurements recorded at the peak hour at 1300h.

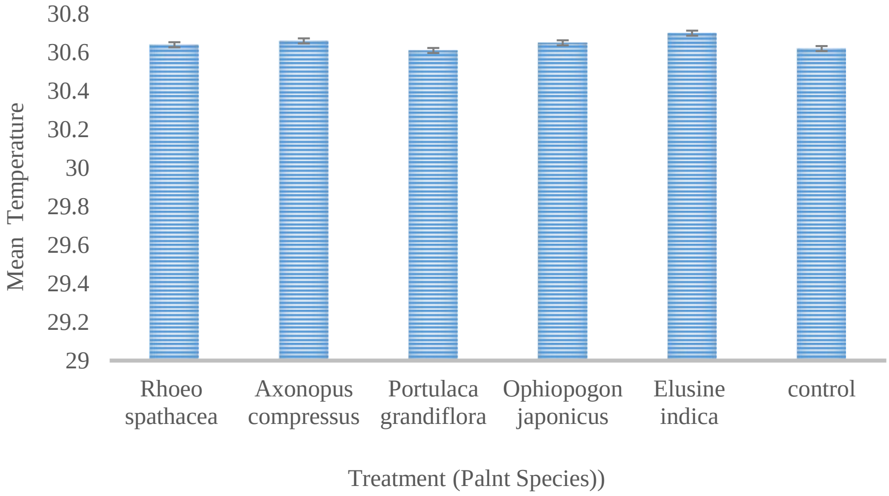


Figure 5.6: Recorded temperature at 20 cm in front of the panels at 1300h

b) Substrate surface temperature

From the recorded substrate temperature for the day it was evident based on the coverage and the foliage density the surface temperature of each plant species varied. At the peak temperature hour at 1300h the recorded temperature is given in the Figure 5.7.

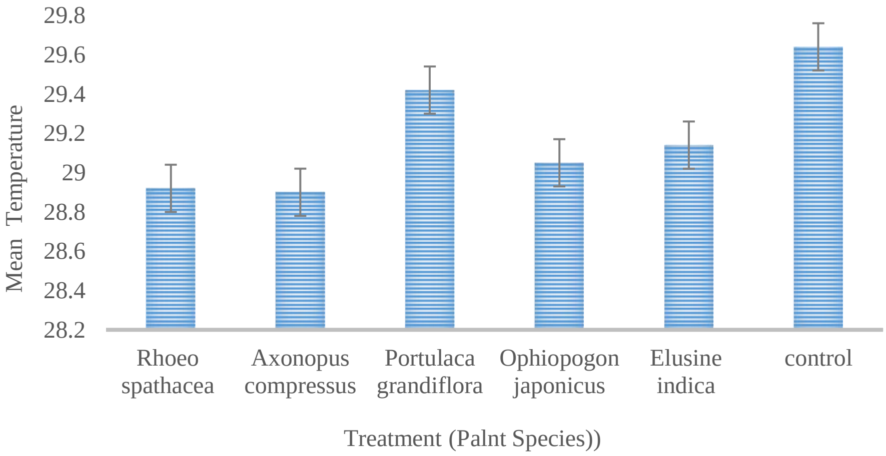


Figure 5.7: Recorded substrate temperature of the panels at 1300h

Substrate temperature of the species *Rhoeo spathecea* and *Axonopus compressus* closely followed each other as the foliage density of the species were higher than the other three species. *Ohiopogan japonicus* species which too had a high foliage density recorded a lower substrate temperature than the control and the *Elusine indica* and *Portulaca grandiflora* species. Similarly, in the study done by Cameron (2015), *Jasminum officinale* and *Lonicera spp* with thicker canopy have been identified with the highest potential for cooling when considering the leaf orientation and leaf area. Therefore, the morphology and the leaf blade size directly affect the thermal regulation potential of the green walls (Raji et al., 2015).

As Tilly et al., (2014) suggests the convection and conduction rate from the leaf surface is increased when the leaf size is reduced. This could have influenced the higher reduction of substrate surface temperature of the panels with *Axonopus compressus* which has smaller leaves yet high leaf density. According to Wong et al., (2010) higher density of foliage and the variation in vegetation colour too influence the cooling effect. Therefore, it can be assumed that the colour variation of the plant species and the density of the foliage has influenced substrate surface temperature reduction of the panels of *Rhoeo spathecea* species.

Similar to the recorded in the substrate temperature measurements the temperature of the backside of the panels too followed a similar pattern. As predicted the temperature recordings of all the panels were lower than the ambient temperature and the substrate surface temperature. Rhoeo spathacea panels and Axonopus compressus panels recorded the highest temperature reduction. This is due to the collective effect of the foliage density (Perkins & Joyce, 2012), effect of shading by leaves (Wong et al.,2010) together with the substrate thickness that lowers the heat conduction to the panel backside. The interactions in leaf areas, geometry and color of leaf and microclimatic parameters such as solar radiation too result in variances in the cooling efficiency (Perini & Oteele, 2012).

The on-site investigation conducted for the shortlisted five species selected from the stage one of the plant selection experiment resulted in shortlisting the two species *Rhoeo spathacea* and *Axonopus compressues* as the best plants for the proposed modular vertical greening system.

5.4 Extended plant selection on-site investigation

On-site plant selection experiment was further extended where the shortlisted two species were further observed for their performance in vertical plane in natural exposed conditions.

Figure 5.8: On-site investigation of selected two plant species

Similar to the previous stage five prototypes of each plant species were fixed vertically to a west facing wall and the observation was continued for two months (Figure 5.8). In evaluating the thermal performance, temperature data were measured for 48 hours using Graphtec midi GL820 datalogger following the same procedure and measurement points mentioned at the stage one thermal performance analysis of the existing vertical greening systems; on the wall surface shaded from each modular panel type, internal wall surface directly behind. Same measurements were taken on the adjacent bare wall surface and the internal surface of the bare wall.

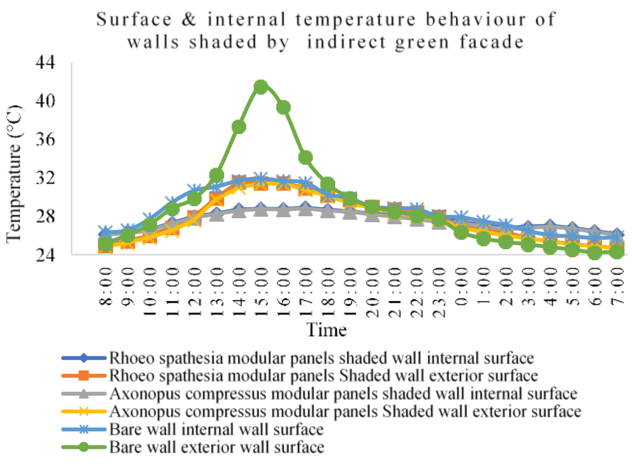
5.4.1 Results of the extended plant selection investigation

Both the plant species *Rhoeo spathacea* and *Axonopus compressus* survived well in the exposed condition. Yet with the growth *Rhoeo spathacea* species signified an issue in maintenance with its increasing height and weight overtime. Comparatively *Axonopus compressus* was better in survival as well as maintenance in terms of its limited height and weight.

5.4.2 Thermal performance of the investigated plant modules

The temperature difference on the foliage surface of two species was insignificant when compared to each other. The recorded temperature difference of the wall surface temperatures shaded by the modular panel types are shown in fig. 5.9. The maximum temperature difference of shaded external wall surfaces was recorded as 9.97°C and 10.08°C in *Rhoeo spathacea* and *Axonopus compressus* modular panels respectively compared to the bare wall control. In terms of internal surface temperature difference (Figure 5.9) a maximum temperature difference of 3.11°C and 3.15°C were recorded respectively in *Rhoeo spathacea* and *Axonopus compressus* modular panels compared to the bare wall control.

As stated by Mazzali et al., *(*2013) plant selection for vertical greening must be done considering not only the aesthetics but also the microclimatic condition, cultivation system, exposure to the sun and etc. Safikhani et al., (2014) and Rayner et al., (2010) further elaborates that life cycle, morphological characteristics, adaptability to climatic condition, depth of the roots, space management, installation and maintenance too become vital in the plant selection process. Based on the results of the extended plant selection study and the observations *Axonopus compressus* was selected as the plant species for the proposed modular panel vertical greening system.



Maximum temperature reduction compared to bare wall control		
	Exterior Wall surface Temp.	Interior Wall surface Temp.
Axonopus compressus	10.08°C	3.15°C
Rhoeo spathacea	9.97°C	3.11°C

Figure 5.9: Results of the thermal performance on-site investigation of the prototype green panels

5.5 Selection of growth media for the green panels

Based on the literature and following the on-site experiments done at early stages of the research coir fiber was selected as the main component of the growth medium. Compost and subsoil were mixed to coir fiber in 1:1/2: 1/4 coir: compost: soil proportion to enrich the growth media. Sand was mixed to enhance the porosity thus the permeability of the mix. Handful of crushed construction waste, remains of sieved sand too was used as a sustainable solution to enhance the water permeability.

5.5.1 Moisture content and dry density of growth media

Different mix proportions of coir fibre and sand were tested in lab condition for permeability, dry density and moisture content to select the best mix. Five mix samples; two samples representing each mix type were created with different coir: sand ratios while keeping the compost and subsoil ratios constant. Each sample was saturated for 48 hours prior to obtain the weight of the wet mix. Consequently, the samples were oven dried for 24 hours to obtain their dry weight. Using the collected data, the dry density and the moisture content of the samples were calculated.

Preparing the growth media mix samples

Preparing to saturate the samples

Weighing the saturated mix samples

Weighing the dry mix samples

Figure 5.10: Measuring the wet weight and dry weight of the samples

Using the collected data, the dry density and moisture content of the samples were calculated (Table 5.1).

Table 5.1: Wet weight and dry weight of the tested samples

Soil sample	Mix design (Sand: Coir)	Wet weight of mix	Dry weight of mix
1	0: 1	44.27	4.31
2	1: 1	31.46	53.195
3	1: 2	36.595	43.015
4	1: 3	36.575	29.66
5	1: 4	36.585	27.08

Equations 1 and 2 were employed to calculate the moisture content and dry density

$$\text{-}\ Moisture\ content\ = weight\ of\ \frac{water}{Solid} \tag{1}$$

$$\text{-}Dry\ density\ \ \gamma d\ \ \ = \frac{bulk\ volume}{1{+}moisture\ content} \tag{2}$$

Using the wet weight and dry weight of each sample the moisture content and the dry density was calculated (Table 5.2) which was used to draw the compaction curve for comparison (Figure 5.11).

Table 5.2: Calculated moisture content and dry density of the tested samples

Soil sample	Mix design (Sand: Coir)	Moisture content	Dry density
1	0: 1	7.692	0.0687
2	1: 1	0.5914	0.6778
3	1: 2	0.8506	0.5024
4	1: 3	1.2325	0.368
5	1: 4	1.369	0.2829

Since the moisture content was too high and the dry density was very low the first sample which contained no sand was not considered for the comparison. As per the literature findings plants grow better in media which is soft enough to allow root development yet sufficiently compacted allowing a good root-soil contact. Here the samples were tested at saturated level which gave the saturation line. From the comparison sample 03 which was sand: coir 1:2 ratio displayed the intermediate compaction compared to the other three samples.

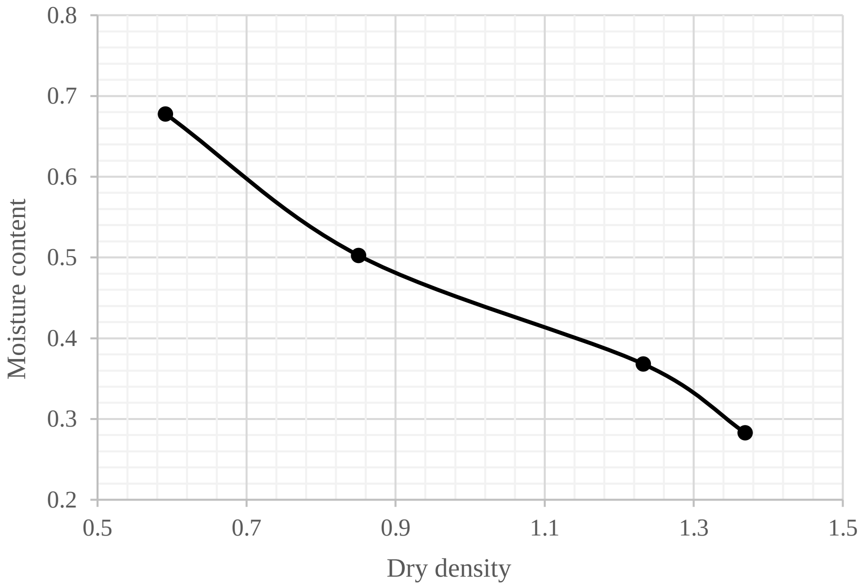
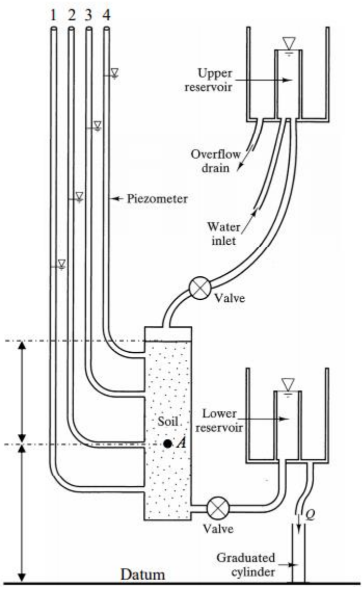


Figure 5.11: Compaction graph of the tested growth media samples

5.5.2 Permeability of the samples

Following the dry density and moisture content test permeability test for the five mix samples were carried out in lab condition using the constant head permeability set up (Figure 5.12). Eight readings were taken for each sample at eight different heights.



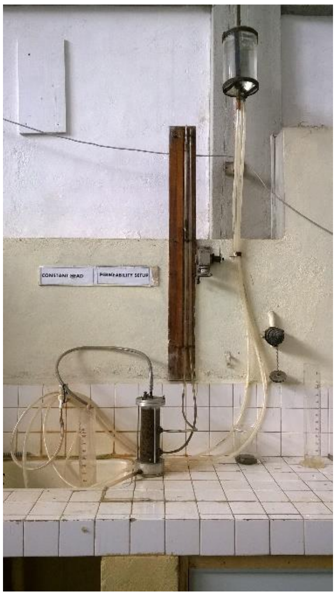


Figure 5.12: Conducting the permeability test for the growth media mix samples

Table 5.3: Collected data and calculated rate of flow of coir: sand 1:1 sample

S/W	h_1 (cm)	h_2 (cm)	Δh (cm)	V cm^3	Time (sec)	Rate of Flow cm^3/s
1	73.3	100	26.7	100	50.6	1.976
2	71.4	97.5	26.1	100	51.8	1.930
3	69.4	95.3	25.9	100	52.47	1.905
4	67.3	92.7	25.7	100	52.78	1.894
5	65.2	90.3	25	100	53.57	1.866
6	62.7	87.4	24.7	100	53.91	1.835
7	60.7	84.9	24.2	100	55.65	1.796
8	58.8	82.4	23.6	100	56.28	1.776

The graph of rate of flow then was obtained for each sample based on the calculation Table 5.3. Using the collected data rate of flow for each reading was calculated which was used to draw the graph (figure 5.13). The graph drawn was then used to calculate the coefficient of permeability of each sample using the equation 3.

$$Q = \left(\frac{KA}{L}\right) h \qquad (3)$$

Where Q is the rate of flow, K is coefficient of permeability, A is cross sectional area of the specimen, L is the length of the specimen and h is constant head causing flow.

A = $4.5364 \times 10^{-3} m^2$ and L= 93×10^{-3}m

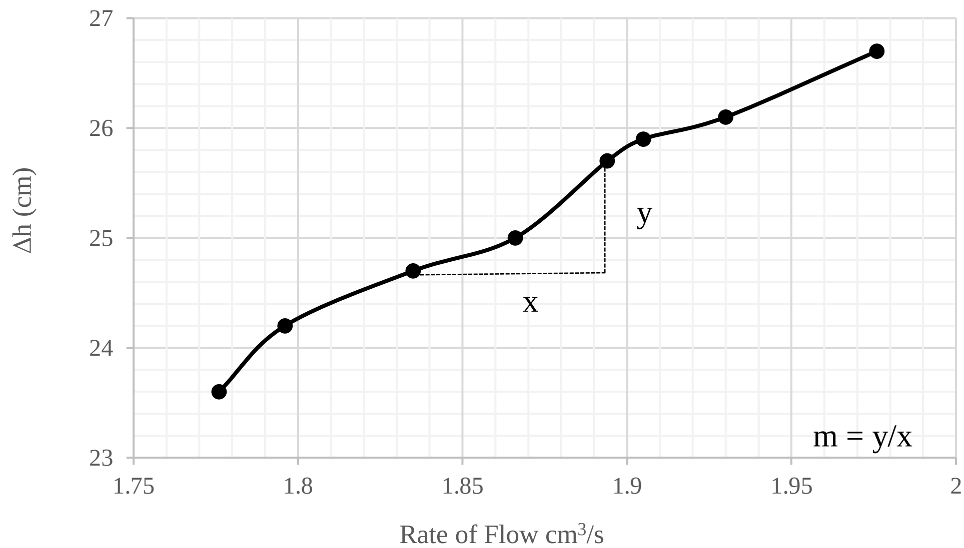


Figure 5.13: The graph of Δh and rate of flow for sample coir: sand 1:1

Accordingly, the permeability of the five mix samples were calculated which is given in the Table 5.4.

Table 5.4: Permeability of the five mix samples

Soil sample	Mix design (Sand: Coir)	Permeability (cm/s)
1	1:0	0.117145
2	1:1	0.143505
3	2:1	0.196
4	3:1	0.17083
5	4:1	0.1177

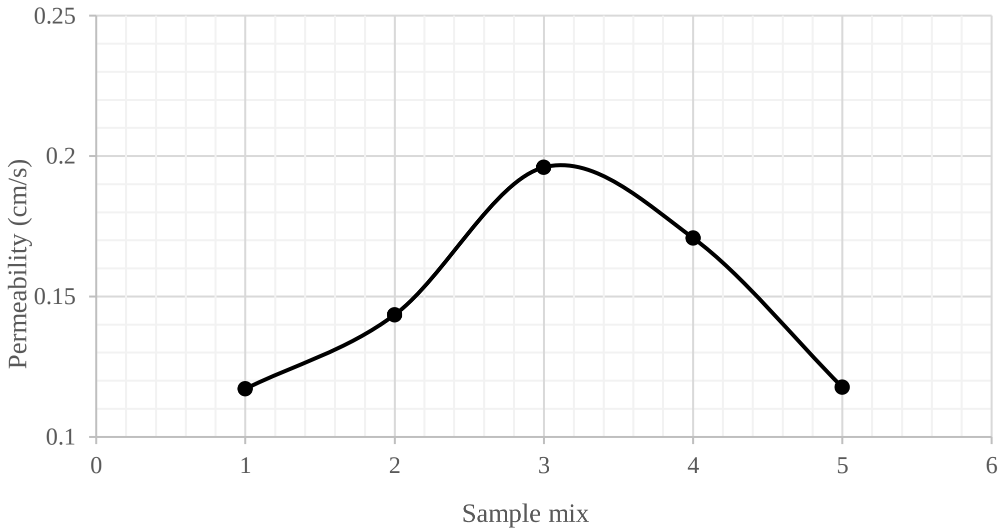


Figure 5.14: Permeability of the five mix samples

From the tested five mix samples, sample 03 which contained coir: sand in 2:1 proportion displayed the best permeability (Figure 5.14). Permeability is a vital factor in deciding the growth media. Since coir which was selected as the main component of the growth media has a high-water retaining capacity, excessive water retention can cause deterioration of the roots therefore the plant health. Therefore, it was decided to select the sample mix with the best permeability. Considering the permeability, dry density, moisture content, bulk weight 2:1 coir: sand sample was selected as the growth media.

5.6 Chapter summery

This chapter focused on the plant selection and the growth media selection for the proposed modular panel vertical greening system. Plant selection for a vertical greening system needs to be considered with the facts such as plant life cycle, adaptability to the vertical living in exposed conditions, root system, survival and etc. Moreover, when developing an economical vertical greening system, availability of the plant species, easy access and less cost also are vital considerations. Therefore, on-site experiments and observations were carried out for eight months to select the best suitable plant species for the proposed vertical greening system out of the selected and shortlisted twelve plant species which were less costly, readily available. From the field studies and observations *Axonopus compressus* species was selected as the best suited plant for the proposed modular panel vertical greening system.

When developing a modular panel system for vertical greening, growth media to be used too become highly important. In different vertical greening systems, different growth media has been used. Substrate for vertical greening can be both organic and inorganic with mineral nutrients. Some systems may be developed as soilless or as hydroponics. The proposed modular panel vertical greening system is to be developed to use organic growth medium as the substrate. Maintaining a lower weight for each panel is needed for the maintenance and easy handling of the panels. Therefore, having a substrate which is low in weight and less costly is required while fulfilling all the other requirements of a substrate. Literature and pilot surveys identifies coir fiber as the best main component for the growth media mixed with compost and subsoil in 1: ½: ¼ ratio. Plant roots which grow in compacted soils may transverse the impenetrable soil by the bio pores and cracks. Further for plants to grow in best condition intermediate bulk density is appropriate which is soft enough to enable better root development yet compact enough to enable the contact between soil and roof. Therefore, mixing of soil to the growth media was important to improve the compactness and permeability of the growth media. Through field studies and laboratory testing it was identified 2:1 coir: sand ratio was the best mix ratio for the proposed vertical greening system.

6. DEVELOPING A GREEN PANEL AS A MODULE OF A SUSTAINABLE EXTERNAL GREEN SKIN IN TROPICAL CONTEXT

6.1 Introduction to the chapter

Use of double skin envelop is still a developing design intervention in all over the world. However, increasing number of buildings and urban density which cause the declination of greenery urge the need of promoting vertical greenery in the city. Unawareness and the lack of technology has led to less use of vertical greening. The proposed green wall panel system will be a sustainable solution as a double skin intervention that adopt novel green concepts while promoting indoor comfort as well as improving outdoor environment. Modular panel system will allow for easy replacement and maintenance of the external green skin.

Green walls systems have the disadvantage of being expensive and hard to maintain. The proposed green wall is designed as a modular panel system, which allows easy handling and maintenance, which also is possible to install this external envelop even to existing single leaf wall. Further the proposed system is advantageous as the walling system can be easily introduced to existing structures and requires less expertise in terms of technical aspects. The proposed wall panel system is supported by a steel framework, which is easy to fix and the panels that can be handled separately allows easy installation and minimum technical support while allowing easy replacement of panels when required.

6.2 Development of the modular panel

The modular panel development stage was done as an experimental study at the university premises. Durability, easy handling and thermal behaviour were the main considerations in designing and developing the modular panel. The vegetated green panel modular wall system was designed to be installed separately as an external double skin using a steel framework without any disturbance to the existing structure. The weight of a fully-grown wall panel was planned to be less than 20kg making it possible to be handled easily with less labor force. A strong durable material like fiber is appropriate for the construction of the wall panel considering its strength, water resistance and durability.

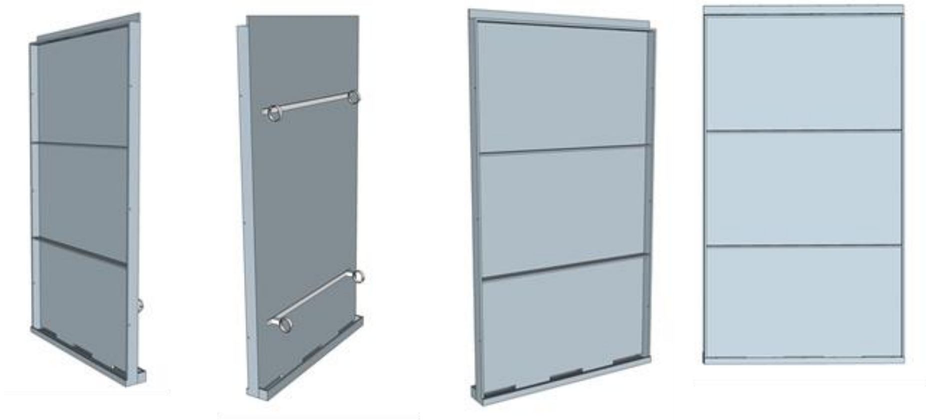


Figure 6.1: Designed modular panel for the proposed vertical greening system

The size of basic a panel was decided to be 600mm (width) x 900mm (height) as shown in Figure 6.2. Anti-slip projections were created in two intermediate levels with the intention of holding the lightweight growing medium. Water inlets and outlets were created at top and bottom of the panel for irrigation purposes whereas a projected tray at the bottom backside was designed to collect excess water dripped from the panel (Figure 6.2).

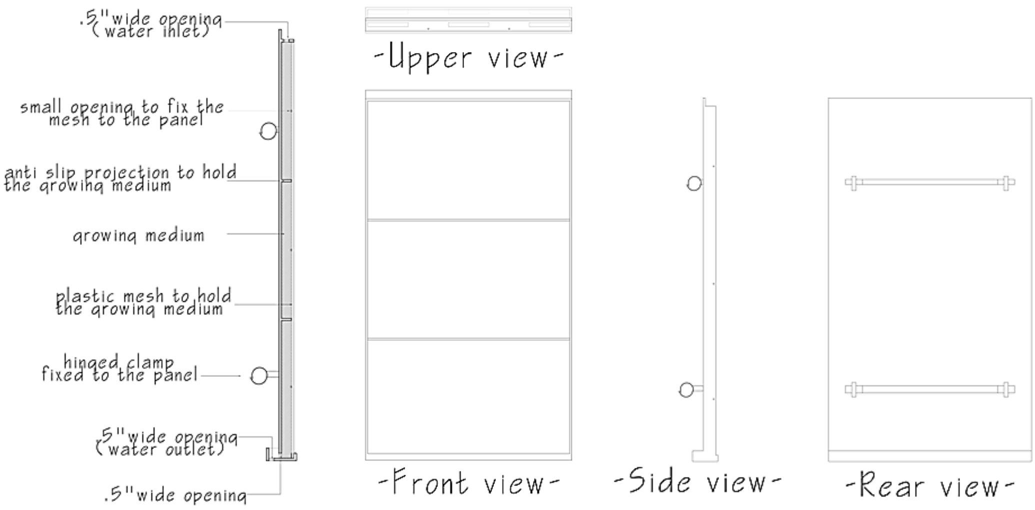


Figure 6.2: Details of the proposed panel

As per the design first a prototype panel was made out of modeling board. Following that the actual scale models were then prepared using fiber as the material based on the strength, durability and water resistance (Figure 6.3).

Figure 6.3: Making of the actual modular panel

6.2.1 Preparation of the vegetated panels

The selected plant species *Axonopus compressus* was grown in controlled conditions till the rooting was properly done and well linked with the growing medium (Figure 6.4). Once the plants were well established, the panels were kept in exposed condition for two weeks to check the survival and tolerance.

Figure 6.4: Development of the vegetated panels

6.2.2 Pilot thermal performance analysis of the individual panels

Experimental study was done at the civil engineering department premises using actual mini scale house models constructed for previous research as shown in Figure 6.5. Temperature measurement points are shown in Figure 6.6.

Figure 6.5: Thermal performance analysis of the panels

Thermal performance of the panels was measured for 48hrs on a clear day using Graphtec midi GL820 datalogger. following the same procedure and measurement points as in the previous stages.

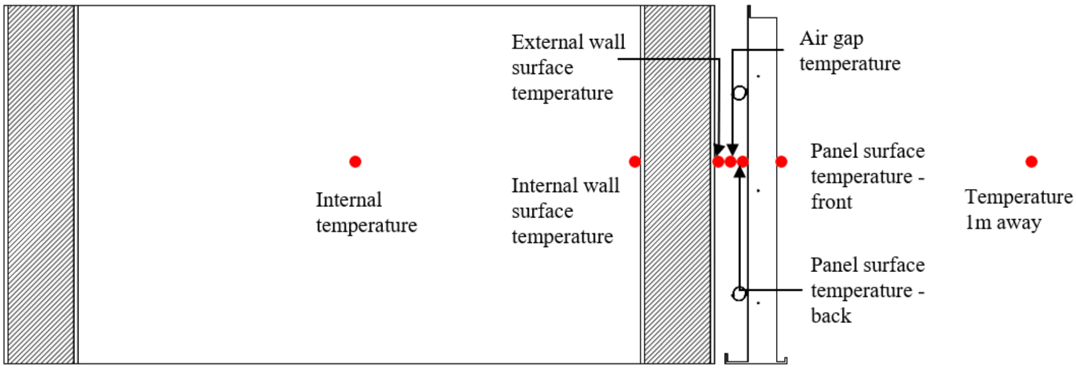


Figure 6.6: Temperature measurement points

Results of the pilot thermal performance analysis of the individual panels

The temperature difference of the shaded wall outside and inside compared to the bare wall control was considerably high recording a maximum temperature difference of 14.10^{o}C in external side of the walls whereas 6.65^{o}C (Figure 6.7) temperature difference in internal side of the walls. Internal air temperature inside the space shaded from the vertical green wall was recorded as 30.8ºC which was 2.2ºC lower than the shaded outside ambient air temperature. Through the findings it was evident that the green wall panels were able to maintain a lower surface temperature and lower internal temperature at the peak hours of the day helping to reduce the thermal discomfort caused by the higher temperatures.

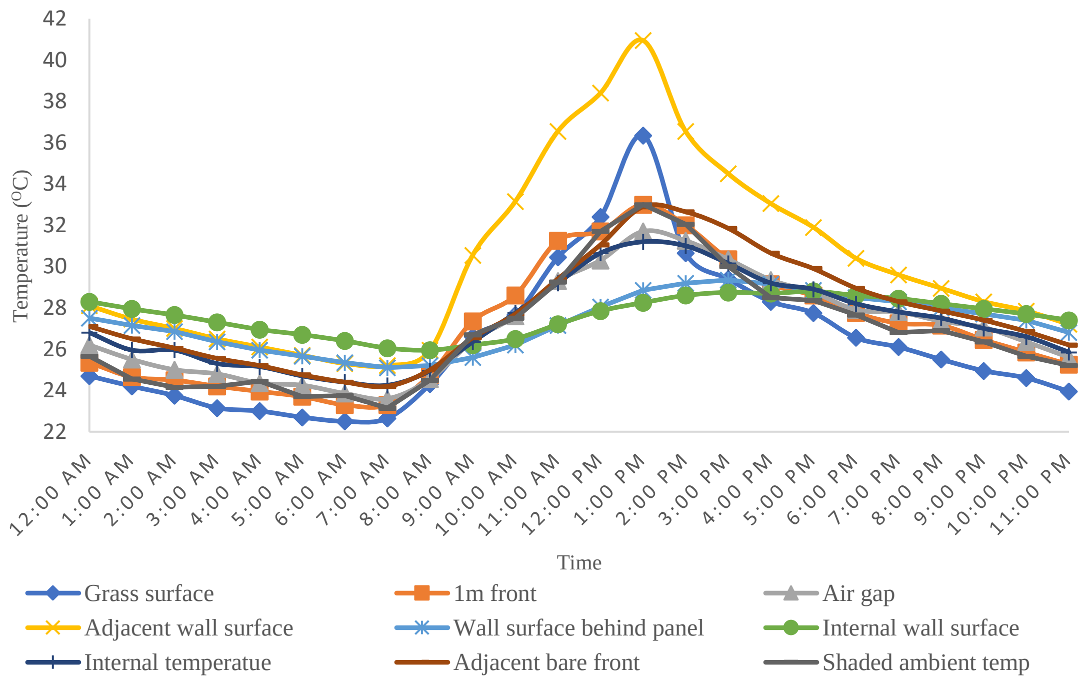


Figure 6.7: Results of the thermal performance analysis of the individual panels

6.3 Development of the vertical green wall system

Following the development of the panels the design and development of the walling system in actual scale was initiated. The vegetated green panel modular wall system is designed to be installed separately as an external double skin using a steel framework without any disturbance to the existing structure as shown in Figure 6.8. Once the individual panels are ready they can be fixed as an external skin to the wall using the steel framework. The inbuilt hooks at the rear side of the panels are used to hang the panels separately to the steel framework.

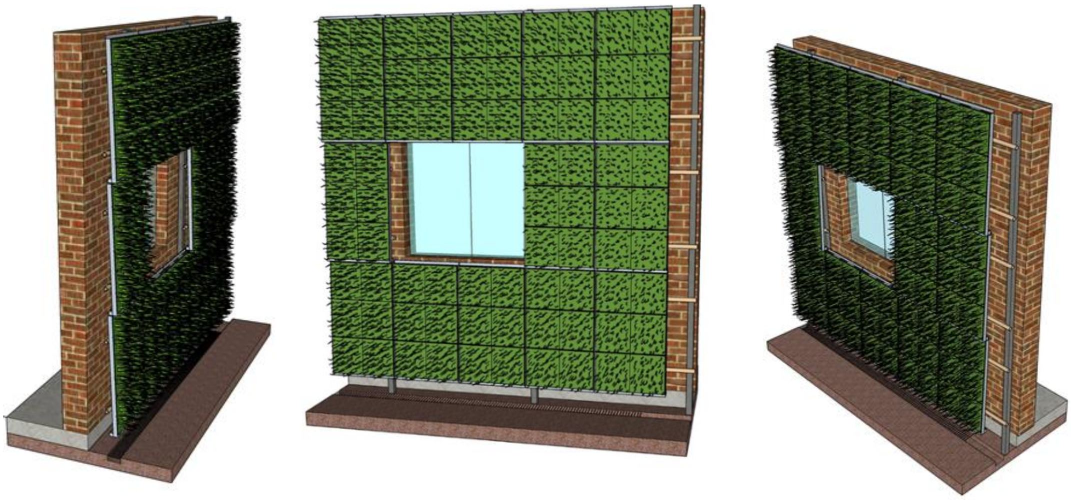


Figure 6.8: Proposed modular panel green wall system

Considering all the above facts the actual scaled model of the proposed modular panel vertical greenery system was set up at the university premises for further studies. In developing the system, it is needed to separate the living wall and the building wall to avoid potential issues related to moisture. This air gap also helps in further minimising the heat transfer towards the building interior. However, the air gap maintained in between the façade and the vertical greening has to be maintained at an optimum distance to achieve this thermal benefit. Therefore, for this study the gap was maintained as five inches.

Figure 6.9: Setting up the modular panel green wall system

Once the panels were established in vertical plane as a wall next step was to identify the irrigation requirement for the proposed vertical greening system.

6.3.1 Investigating the irrigation sequence

Next step was to identify a proper irrigation sequence for the vertical greening system. The field capacity of the growth media was calculated using the volume basis lab testing. The test results indicated the field capacity of the selected growth media to be 59% on volume basis where the moisture content at field capacity was calculated as 0.8506. Following the field capacity test, moisture content of the growth mix at the permanent wilting point was calculated based on the weight of dry mix and wet mix. Nine sample panels were created for the testing using the selected growth media mix and the plant species (Figure 6.10). Until the plants are well established the panels were equally irrigated. One panel was kept as the control. Other eight panels were subjected to four different irrigations sequences. Each panel was irrigated until the whole panel was completely wet.

Figure 6.10: Field tests conducted for permeant wilting point investigation

Tested irrigation sequences;

T1- Irrigation once in 02 days

T2- Irrigation once in 04 days

T3- Irrigation once in 06 days

T4- Irrigation once in 08 days

Three samples from the panel which was at the permanent wilting point was taken to measure the dry weight and the wet weight to calculate the average moisture content at permanent wilting point.

Table 6.1: Measured wet and dry weight for permanent wilting point test

Sample	weight of wet mix	weight of dry mix
1	130.9	129.05
2	105.09	104.09
3	106.05	104.69

Accordingly, moisture content at permanent wilting point was calculated as 0.0122. As per the agricultural recommendation plants should be irrigated at or before the moisture content reaches 50% in-between the field capacity moisture content and permanent wilting point. Based on the findings the average moisture content must be maintained at 0.4192. Hence, under normal weather conditions irrigating the panels once in eight days till the panels reach the field capacity would be required.

6.3.2 Developing the irrigation system

Several factors were considered in selecting the irrigation type for the proposed vertical greening system. Since the main aim of the research was to develop an economical and user friendly vertical green wall least costly method of irrigation was needed to be established.

Irrigation system selection consideration

- Economical, availability of pipes and other equipment
- Convenience in fixing, operating and maintaining
- Durability and minimum wastage

Watering system considerations

- Type of plant, plant life cycle and coverage
- Gravitational capacity of plants
- Growth media mix and thickness
- Water supply frequency and efficiency
- Panel angle and length

From the available and commonly used watering system types such as drip irrigation, sprinklers, sub surface and surface irrigation systems drip irrigation was selected as the suitable watering system for the green wall considering the above aspects.

6.3.3 Investigating the panel water requirement

Once selecting the watering system and the irrigation sequence, next the water requirement for a single panel was investigated. Each panel was watered using the drip irrigation method where each individual panel was watered using five drip outlets so the total panel would equally get watered. The time and amount of water needed until the total panel is fully wet was measured whereas the excess water quantity that dripped out from the panel too was measured in order to avoid excessive watering (Figure 6.11).

Figure 6.11: Measuring the water requirement of a single panel

The below data were measured through the field study;

Amount of water required for a single panel to reach saturated level- 6.12L

Time taken to reach saturated level- 18 minutes 02 seconds

Amount of water dripped as excess- 3.85L

Thus, the amount of actual water requirement of a panel- 2.27L

Time period to supply required amount of water to an individual panel – 7mints.

Once the actual scale panels were fixed vertically and were irrigated until the saturated conditions a single panel absorbed 6.12L in 18 minutes and 02 seconds. The gravitational water quantity was collected and measured as 3.85L. Accordingly, the total water requirement of a panel to reach field capacity was identified as 2.27L. Therefore, when using the selected drip irrigation, the panels needed to be irrigated for 7 minutes.

6.4 Thermal performance evaluation of the proposed vertical greening system

Once the field data required were gathered and analyzed the modular panel green wall was established at a west facing façade to observe its performance in actual situation. The thermal performance was measured following the same procedure as early stages (Figure 6.12).

Figure 6.12: Experimental setup of the vertical modular panel green wall system

Similar to the results obtained in pervious mini scale house model thermal evaluation, the temperature difference of the shaded wall outside and inside compared to the bare wall control was considerably high recording a maximum temperature difference of 17.26^{o}C in external side of the walls whereas 7.89^{o}C (fig. 6.13) temperature difference in internal side of the walls. Internal air temperature inside the space shaded from the vertical green wall was recorded as 30.24^{o}C which was 2.89^{o}C lower than the shaded outside ambient air temperature.

Similar to the results obtained in the experimented context, 20.8^{o}C in exterior and 7.7^{o}C in interior surface temperature reduction whereas 3.1^{o}C reduction in air temperature in the air layer between the wall and the vertical greening compared to ambient air temperature has been recorded by a living wall system during a study conducted in China (Cameron et al, 2014). Therefore, findings confirmed that the proposed vertical greening system has the ability to maintain a lower surface temperature and lower internal temperature at the peak hours of the day helping to reduce the thermal discomfort caused by the higher temperatures.

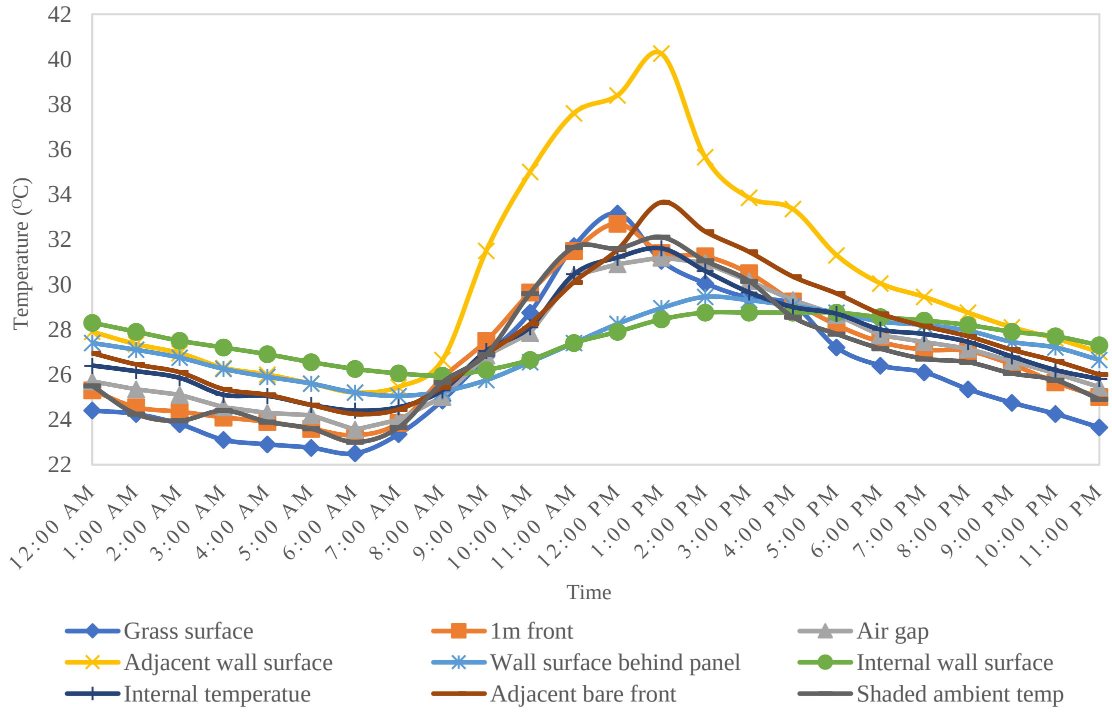


Figure 6.13: Thermal performance of the proposed green wall system

6.5 Chapter summery

With the rising requirement in reducing the increment of air temperature and cooling load energy consumption parallel to the global environmental and energy crisis, building related solutions to address this need is experimented in global context. As identified through the literature the potential of surface temperature reduction and the internal air temperature reduction by integrating vertical greenery is directly helping in reducing cooling energy requirement in the buildings.

Many of the available living walls are complex and expensive structures that consists of a supportive structure and attachments. In developing such a system, it is needed to separate the living wall and the building wall to avoid potential issues related to moisture. Planting option in-situ after constructing the structure or planting ex-situ and fixing pre-vegetated plants (Charoenkit & Yiemwattana, 2016) and a proper irrigation system (mazzali et al., 2013) must be worked out.

This chapter presented the experimental studies conducted to design and install the proposed modular vertical greening system, designing of irrigation system and irrigation sequence and the potential surface and indoor air temperature reduction by integrating the proposed system. The results of the experiments signify the potentials of the developed modular vertical greening system as an economic VGS system which has a high thermal benefit in terms of reducing the energy consumption of buildings for cooling purpose.

7. PERFORMANCE EVALUATION OF VERTICAL GREENING IMPLEMENTATION IN MICRO AND MACRO CONTEXTS

7.1 Introduction to the chapter

Maintaining the indoor and outdoor thermal comfort and the mean temperature levels is of vital importance for the human wellbeing due to the current global issue of temperature rise, especially in urban contexts. In terms of building scale improving the thermal performance of the building envelop to reduce the external gain has the potential to make buildings energy efficient by reducing the operational costs for cooling and heating purposes while also minimizing the building associated negative environmental impacts. On the other hand, in urban scale minimising the UHI effect has a greater impact on mitigating the temperature rise in urban contexts. Thus, investigating and improving the thermal performance of the proposed vertical greening integration is required to compare the advantage of such integration.

In this context, modelling and simulating using different software facilitate identifying the positive and negative impacts of different design integrations done in building scale as well as urban scale on the urban temperature and buildings' internal temperature. Design builder and Envi-met are such two software which enable simulating and calculating different parameters in buildings and urbanities. This chapter brings out the results of experimental simulation studies conducted using the two software.

7.2 Evaluating the benefits of the proposed VGS in building context

To investigate and explore deeply about vertical green walls and their thermal benefits microclimatic models can be applied for simulation studies. As per the findings by Jänicke et al. (2015) the slight deviation between the simulations and observations are almost negligible thus enabling to come to conclusions using the simulation outcome. In this study, vertical greening was introduced to the building façade as an external layer to the building façade. For simulations layers and the properties of the green wall system was given as input data for the newly introduced layer to the building model to represent the vertical greening system.

7.2.1 Simulation software: Design builder

Design builder which is one of the most comprehensive user interfaces for Energy Plus dynamic thermal simulation engine (Rahman et al., 2010) is used for the simulation for the study to identify the potential energy saving with integration of vertical greening in local context. Design builder can be introduced as a simulation software program widely used in present day to conduct energy consumption calculations of buildings.

This software enables simulating range of environmental performance data namely comfort conditions, energy consumption, carbon emission, day light luminance and etc. Design builder utilizes the dynamic simulation engine "energy plus" to calculate the performance data of the buildings. The software has limitations in terms of inputting geometry of complex nature. Nevertheless, this is regarded as one of the most advanced simulation software programs which provides a greater opportunity to investigate energy consumption data in depth with relevance to existing actual data.

7.2.2 Pilot study using Design builder software

As the pilot study of the design builder simulation, the civil engineering building of the university of Moratuwa was selected as the base case (Figure 7.1). To ensure the model created for study is properly modelled and detailed model validation is required (Rahman et al., 2010).

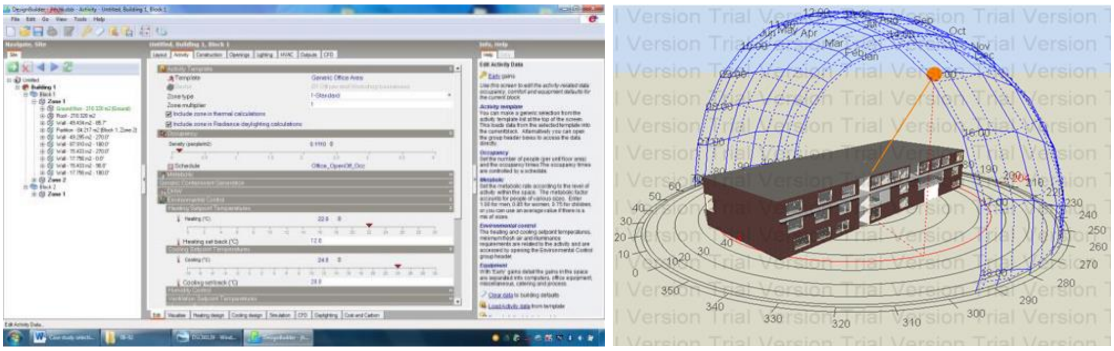
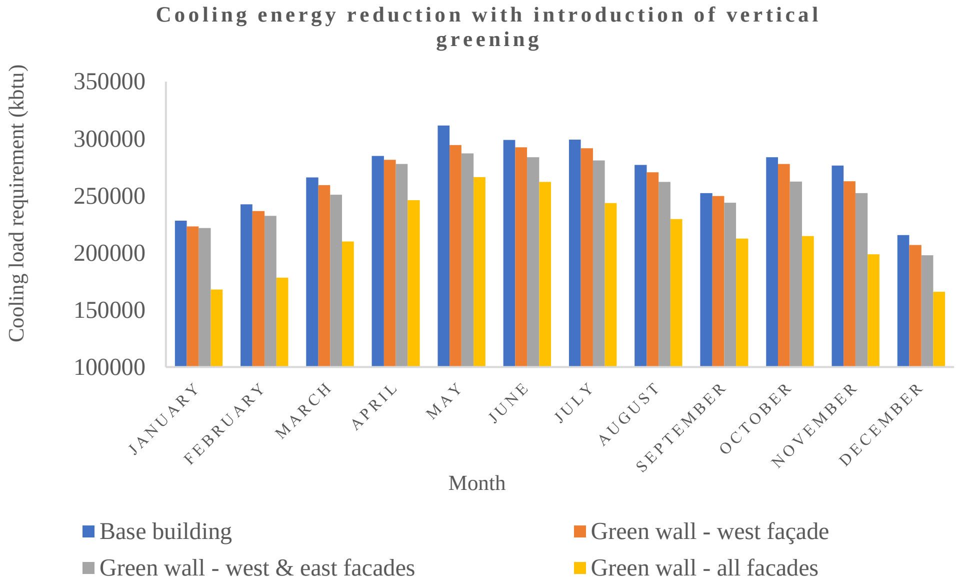


Figure 7.1: Pilot study in building scale

Results of the pilot study

The selected building was modeled using the software and was calibrated to validate the simulation by matching the actual thermal data taken on site and the calibrated data. Keeping this as the base case the building was again simulated with the introduction of vertical greening to each façade as an external layer to the building façade. Layers and the properties of the green wall system was given as input data for the newly introduced layer to the building model to represent the vertical greening system.

The building was simulated with addition of vertical greening to the facades to obtain the total cooling energy requirement for the building operation throughout a year. The results of the simulated cases were compared to the cooling energy requirement of the base case scenario. Also, the thermal behaviour of a typical day was compared in each simulated case.



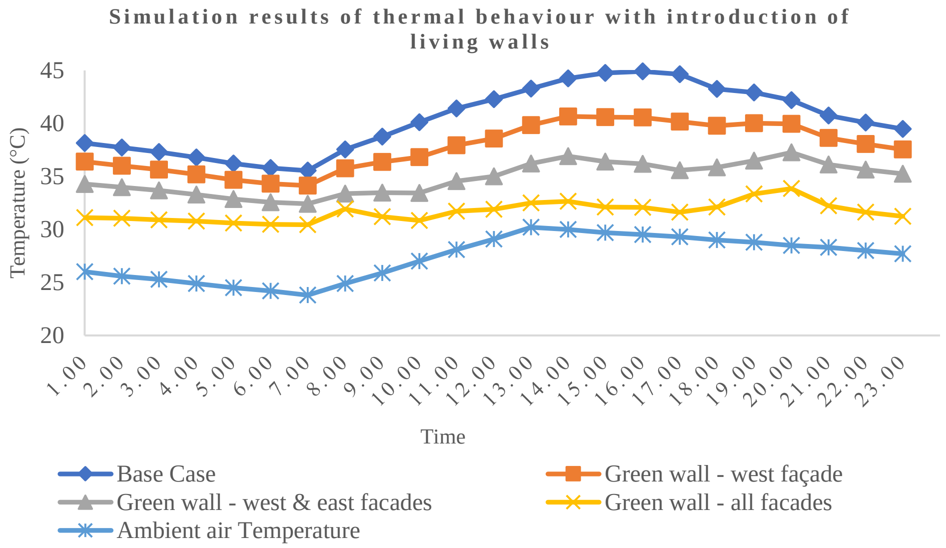


Figure 7.2: Results of the pilot study in building scale

As shown in the Figure 7.2 the simulation results signified a greater reduction in total cooling load requirement throughout the year as well as the internal air temperature behaviour in a typical day with the addition of vertical greening gradually to the building facades. This indicated a higher potential of the proposed vertical greening system to be integrated as a sustainable design solution to overcome the high cooling load requirement of buildings in tropical contexts.

7.2.3 Thermal and energy performance in building context

Following the pilot study two separate simulation studies were conducted to identify the internal air temperature reduction under non-air-conditioned building operation mode and cooling load reduction under air-conditioned building operation mode with vertical greening integration.

a) Simulation of building 01; air temperature behaviour in non-air-conditioned mode

A generic office type building consisting four stories with a 1161m^2 was selected as the first case for the simulation study. Existing building was modelled using the design builder simulation software and was kept as the base case scenario. One office area representing all the office spaces in the building was selected to be simulated with vertical greening. Model was validated by calibrating the thermal measurement with actual thermal measurements. Once validated the same model was introduced with the proposed vertical greening system as a second layer to the outer envelope of the building to obtain the temperature behaviour throughout the day (Figure 7.3).

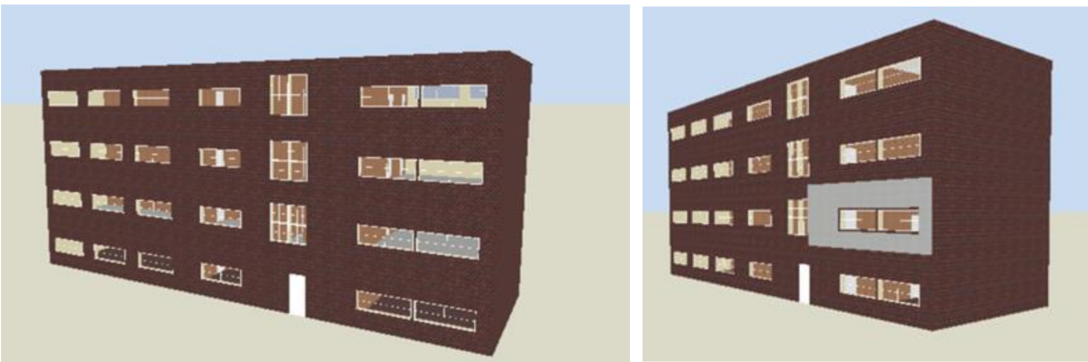


Figure 7.3: Simulated office building for thermal regulation with vertical greening

As shown in the Figure 7.4 with the addition of vertical greening the indoor air temperature behaviour of the simulated office space recorded a lower air temperature during the peak temperature hours with non-air conditioning mode. The space with the vertical greening recorded an average indoor air temperature of 28°C whereas the building in existing condition without vertical greenery recorded an average air temperature of 30.4°C. Average indoor temperature reduction with vertical greenery is therefore 2.4°C. The recorded highest temperature at 1330hrs with no vertical greening is 37.3°C whereas with vertical greenery the peak indoor temperature was recorded only as 30.8°C at 1500hrs which depicts the temperature reduction and the time lag triggered by the vertical greening.

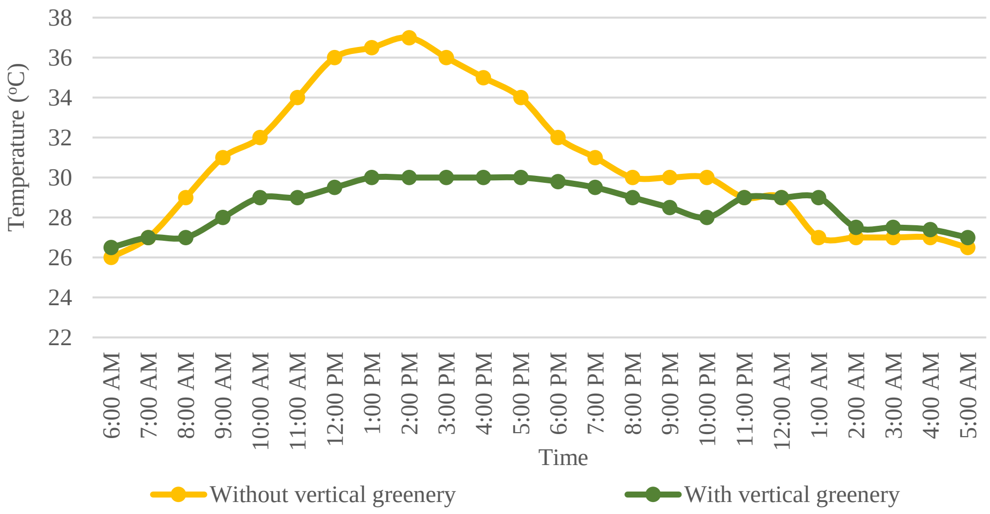


Figure 7.4: Indoor air temperature behaviour of the simulated office space

b) Simulation of building 02; energy consumption in air-conditioned mode

A building in highly urban Colombo context was selected for the energy consumption simulation study. The same building was previously investigated with different double skin interventions to identify best double skin envelop strategy (Rupasinghe, 2015). Therefore, the same building was selected to compare the energy saving potential of integrating vertical greenery as the external skin of the double skin envelop. Weather data for the simulated dates were obtained from the Colombo meteorological department and the actual energy consumption data which was monitored and recorded were obtained from the building administration.

The building was modelled using the software and the collected data were given as the input for the simulation study (Figure 7.5). The model was simulated to obtain the energy consumption of the modelled building and was compared with the actual energy consumption data for the model validation. The actual energy consumption for the simulated day was recorded as 789.85 kWh and the simulated model recorded the energy consumption as 776.23kWh. Therefore, it was assumed that the base case model has credible evidence as a valid model for the simulation with vertical greening integration.

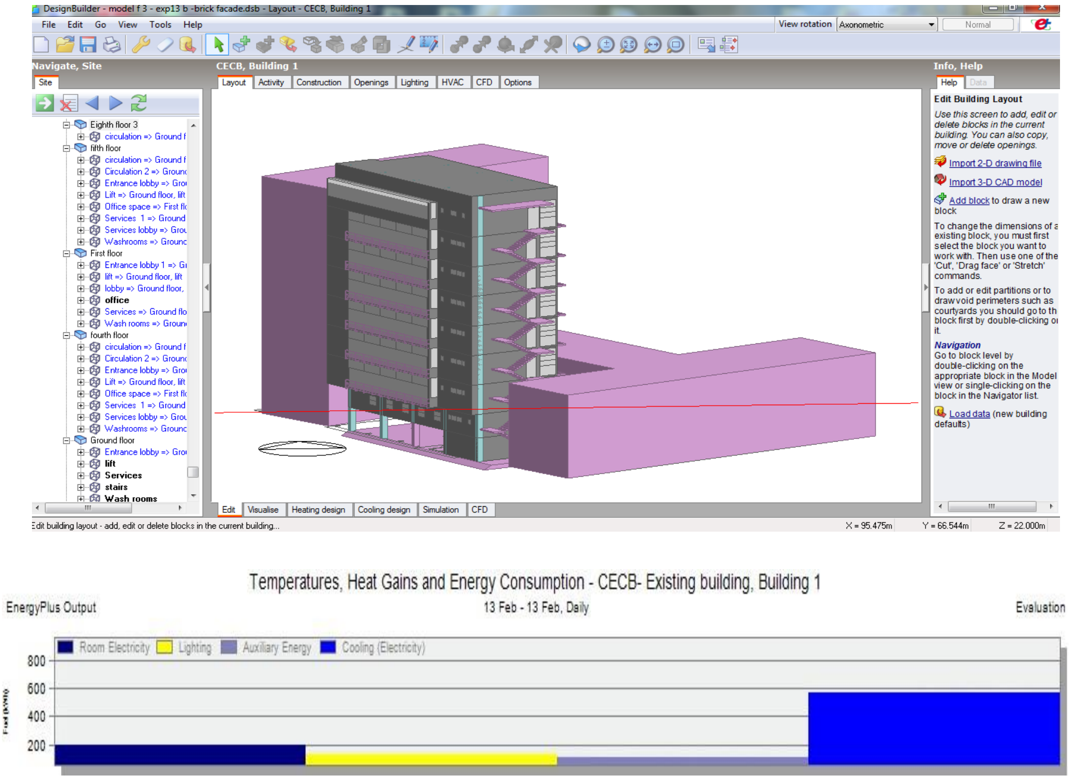


Figure 7.5: Modeled building for energy consumption simulation

Keeping the input data constant facade design was changed as double skin envelop with vertical greening as the external skin of the double skin envelop. Internal skin was kept as it is in the existing condition. The resultant energy performance improvement and cooling load reduction of the simulated model was obtained (Figure 7.5).

Results of the energy consumption simulation study

The previous study has resulted blind brick wall as the best design intervention as a double skin envelop for passive cooling and cooling load reduction. Therefore, the results of the simulation with integrating vertical greening as double skin envelop was compared with the energy reduction potential of blind brick wall. With blind brick wall as the external double skin envelop cooling electricity was recorded to be 346.35kWh recording a significant cooling load reduction of 236.03kWh (Figure 7.6). With vertical greening as the external double skin envelop, cooling electricity was recorded to be 313.82kWh recording a significant cooling load reduction of 268.56kWh (Figure 7.7).

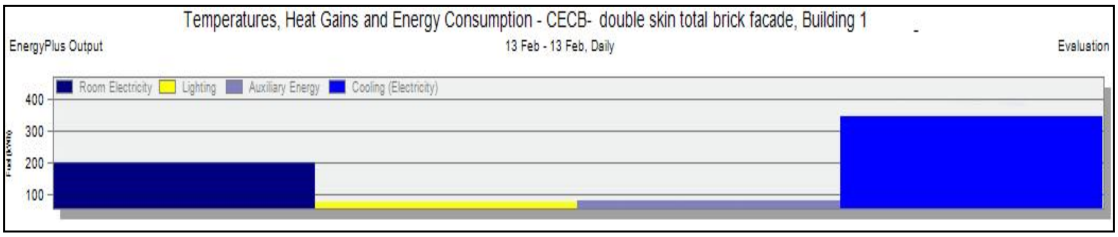


Figure 7.6: Energy consumption with blind brick wall as EDSE

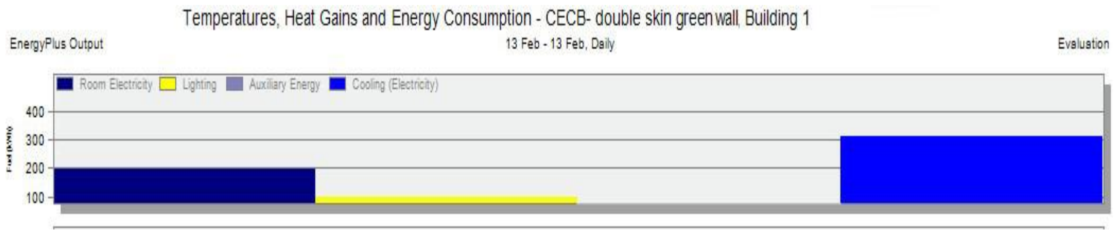


Figure 7.7: Energy consumption with proposed VGS as EDSE

The overall contribution from each intervention is shown in following Table 7.1. It shows that significant energy saving can be expected.

Table 7.1: Comparison of energy consumption with EDSE interventions

Simulated case		Resultant cooling load (kWh)	Deviation from the existing(kWh)	Percentage deviation
A	Existing building (base case)	**582.38**		
B	*Blind brick wall as the EDSE*	346.35	-236.03	40.52%
C	*VGS as EDSE*	313.32	-268.56	46.117%

The simulation was conducted to identify the cooling load reduction potential of integrating vertical greening as a double skin facade. Figure 7.8 indicates the internal air temperature behaviour throughout the day with the two EDSE interventions. As per the results, the energy saving potential due to reduction of cooling loads with the integration of VGS as EDSE signifies to be even higher than blind brick wall as EDSE.

The results further confirm the heat insulative capacity and passive cooling potential of integrating vertical greenery as double skin envelop.

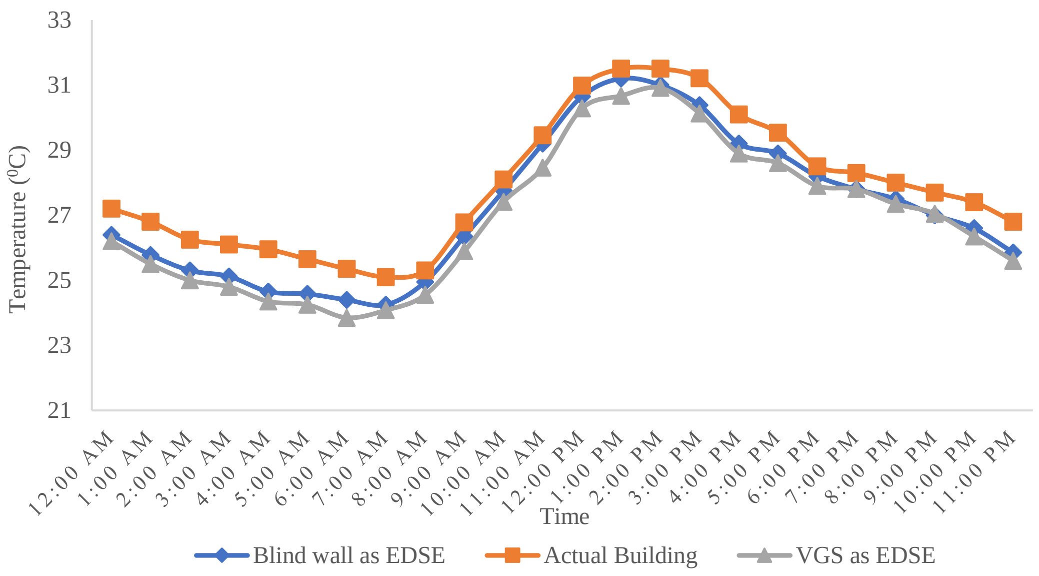


Figure 7.8: Comparison of internal air temperature with EDSE interventions

7.3 Evaluating the benefits of the proposed VGS application in urban context

Following the simulations conducted to identify the benefits of the proposed VGS integration in building scale, simulation studies were conducted to identify the benefits of the proposed VGS to outdoor urban contexts using Envi-met simulation software. From the field studies and on-site experiments conducted at the earlier stages of the research, *Axonopus compressus* was identified as the most suitable plant species for the proposed vertical greening in the tropics. Thus, using *Axonopus compressus* as the plant species for vertical greening simulation studies were conducted in selected urban contexts to identify the benefits of proposed vertical greening in urban context.

7.3.1 Envi-met software:

Envi-met is a CFD based simulation tool that facilitates in calculating urban features such as form, canyon, vegetation etc. that affects the urban microclimate. It is a globally accepted software used for simulation using three dimensional models in different fields such as architecture, city planning, engineering and etc. Envi-met facilitates in finding the required strategies that are needed to obtain the best possible microclimatic conditions in the urban context which is a vital requirement for cities. As Langer et al. (2012) states Envi-met facilitates architects and urban planners with all the information about urban microclimate.

The studies done by Ghaffarianhoseini et al. (2015), Qaid & Ossen (2015) and Gusson et al., (2016) in tropical climate and subtropical climates validates the application of Envi-met software usage for thermal performance analysis in urban scales. Further, the study by Herath et al., (2017) too signifies that the software can be utilized for micro-climatic simulation in tropical climate.

7.3.2 Pilot simulation study in urban context

The initial validation of the Envi-met simulation was conducted by modelling the Civil Engineering department building of University of Moratuwa (Figure 7.9). The actual temperature data were measured for 48 hours with 10 mints intervals which were used to calibrate the simulated model. A new data base was created using the selected plant species as the input data for simulation study. Giving the new data as input for vertical greening the civil engineering department building was simulated as the pilot study to identify the outdoor air temperature reduction with introducing vertical greenery to the building's vertical facades. First the building was simulated in its existing conditions and the outdoor air temperature was obtained. Then, keeping the existing building as the base case, again the building was simulated with introducing vertical greenery and the resultant air temperature data were compared to identify the air temperature difference with and without vertical greenery.

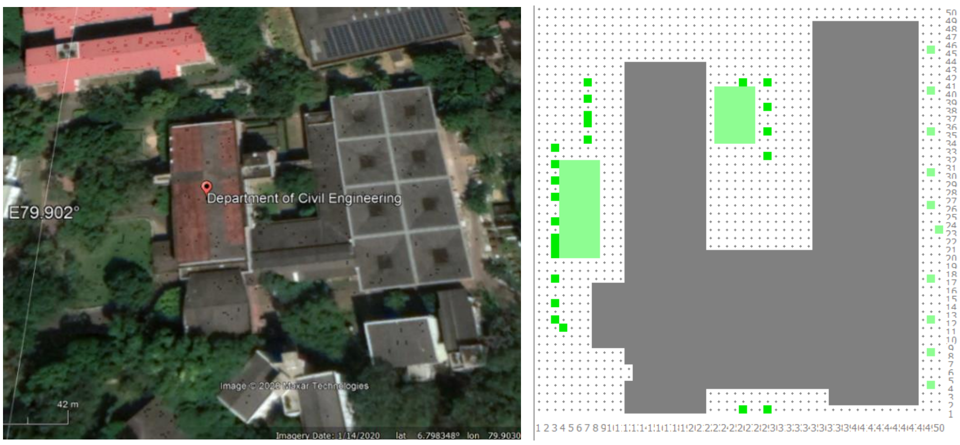


Figure 7.9: Pilot study in evaluating the thermal benefit in urban context

Results of the pilot study

The pilot simulation study was conducted with the aim of familiarizing the software and calibration process. The outdoor temperature measurements obtained through the software simulation was used to calibrate the model comparing with the actual outdoor air temperature measurements to validate the model. However, the difference in outdoor air temperature data obtained with vertical greenery integration and without vertical greenery in this context was very slight when compared to the indoor air temperature difference with and without vertical greenery. The average outdoor air temperature reduction with vertical greenery to the building was recorded to be 0.12^{o}C during the simulated day. This may be due to the fact that the simulated context already has higher percentage of greenery which directly contributes in cooling the outdoor air temperature. As Wong et al., (2010) states vertical greenery may not fundamentally impact on surrounding temperature based on the prevailing conditions.

7.3.3 Thermal performance of the VGS in different urban contexts

For this study three government administrative buildings were selected in three different urban contexts: Colombo, Kandy and Matara. The selected buildings then were modelled and simulated using Envi-met with and without vertical greening integration (Figure 7.10). Sethsiripaya administrative building in Colombo, Kandy urban council building and Matara urban council building were selected as the buildings to be simulated in different urban contexts in the local context which are highly urbanized and populated during the day.

Sethsiripaya administrative building located in Colombo context is a 14-storey building made out of plastered block walls and concrete slab located in the western province at 14m above sea level. Precipitation is high throughout the year and the average annual temperature is 28^{o}C. Matara municipal council building is a 3-storey building made out of plastered block wall with a terracotta tile roofing. Building is located 11m above sea level where annual average temperature is 27^{o}C and the annual rainfall is 2147mm. Kandy municipal council building is a 2-storey building made out of plastered brick walls with a corrugated asbestos sheet roof located 518m above the sea level. Kandy area has a high rainfall throughout the year with an annual rainfall reaching 2083mm and the average annual temperature is 24.5°C.

Figure 7.10: Selected buildings in different urban contexts for simulation study

Existing condition of each building were first simulated as the base case scenarios whereas the same models were again simulated with vertical greenery to compare the potential outdoor urban air temperature reduction (Figure 7.11).

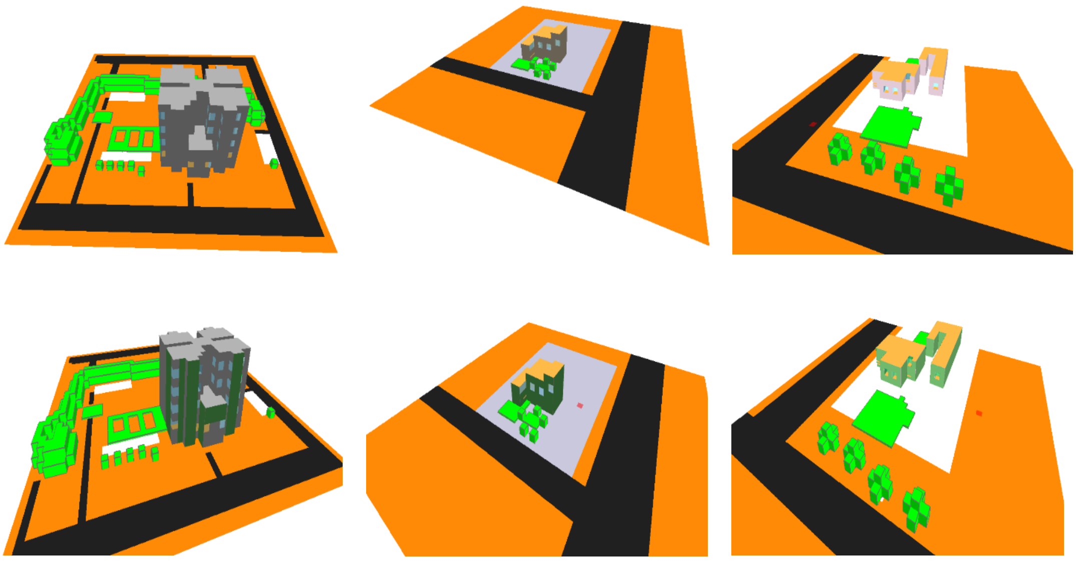


Figure 7.11: Models simulated in Envi-met with and without vertical greenery

a) Sethsiripaya administrative building

Building simulation study of Sethsiripaya administrative building in its prevailing context resulted outside air temperature range as 26.89^{o}C – 33.71^{o}C throughout the day where the peak outdoor air temperature 33.7^{o}C was recorded at 1100hrs. With integrating the proposed vertical greening system to the building envelop as an external skin the outdoor air temperature range recorded as 26.96°C-31.99°C and the peak outdoor air temperature 31.99^{o}C at 1200hrs. Maximum air temperature reduction due to vertical greening intervention is 2.07^{o}C (Figure 7.12a).

b) Matara municipal council building

Building simulation study of Matara municipal council building in its prevailing context resulted outside air temperature range as 26.61°C–31.91°C throughout the day where the peak outdoor air temperature of 31.91°C was recorded at 1100hrs. With integrating the proposed vertical greening system to the building envelop as an external skin the outdoor air temperature range recorded as 26.16°C - 30.53°C and the peak outdoor air temperature 30.53^{o}C at 1300hrs. Maximum air temperature reduction due to vertical greening intervention is 3.29^{o}C (Figure 7.12b).

c) Kandy municipal council building

Building simulation study of Kandy municipal council building in its prevailing context resulted outside air temperature range as 24.85°C - 32.37°C throughout the day where the peak outdoor air temperature 32.37°C was recorded at 1200hrs. With integrating the proposed vertical greening system to the building envelop as an external skin the outdoor air temperature range recorded as 25.04°C - 30.06°C and the peak outdoor air temperature 30.06^{o}C at 1300hrs. Maximum air temperature reduction due to vertical greening intervention is 2.03^{o}C (Figure 7.12c). As Sailor (2006) states cooling effect by water infiltration and evapotranspiration is diminished by impermeable surfaces. This may be the reason for higher surrounding air temperature around the simulated building context which was paved with decorative concrete blocks despite the surrounding vegetation.

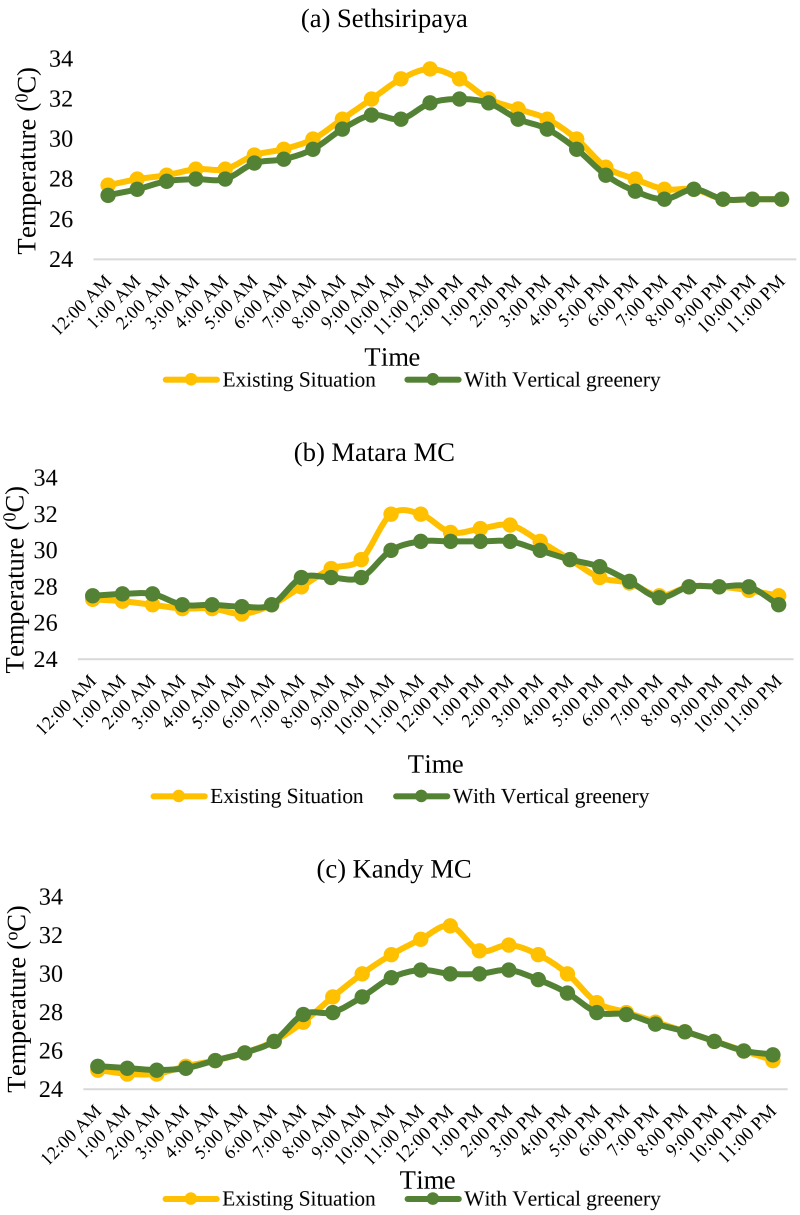


Figure 7.12: Urban air temperature behavior in selected urban contexts after VGS integration

Materials which are high in albedo such as concrete, asphalt roads and brick have high solar absorption capacity which is re-emitted back to the adjacent air layers causing air temperature rise in the surrounding air temperature (Huttner & Bruse, 2008). Further, the study by Takkanon & Chantarangul (2019) has resulted a considerable air temperature difference ranging between 39.00°C – 49.70°C due to unshaded asphalt surfaces. The potential of vegetation in aiding to reduce air temperature has been proved through a study where air temperature has dropped by 3.8⁰C due to surrounding vegetation. The urban canopy created by multi-storey buildings influence UHI effect by absorbing and re-reflecting heat radiation (Mason,2006). Further, tall buildings when densely located reduce the wind velocity which in return diminish the cooling effect as well (Priyadarsini, 2008). Albedo of the paving materials, adjoining roads and construction materials influence the higher air temperature in urban contexts. The selected three buildings for simulation study were concrete construction with either terracotta roof tiles or concrete slabs.

Below Figure 7.13, Figure 7.14 and Figure 7.15 shows the temperature contour maps obtained using LEONARDO visualize tool in ENVI-met which clearly shows the surrounding air temperature difference in each simulated context with and without vertical greening highlighting the significant air temperature reduction with the introduction of vertical greening system.

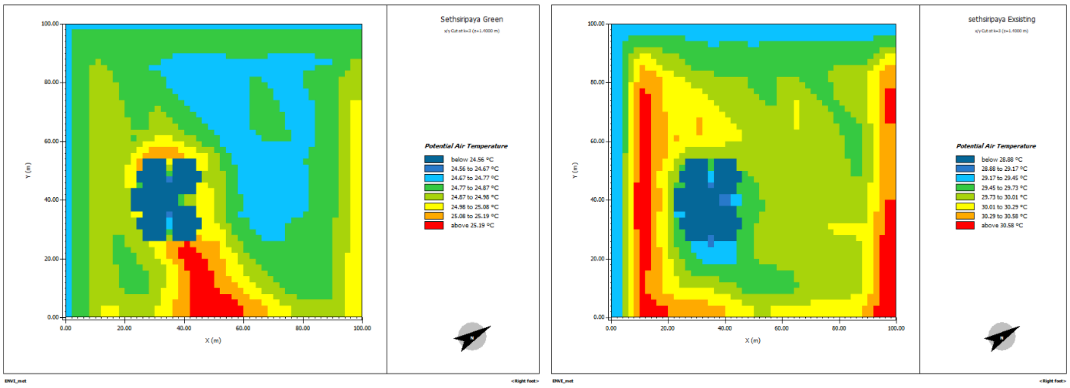


Figure 7.13: Temperature contour map of Sethsiripaya urban context before and after VGS application

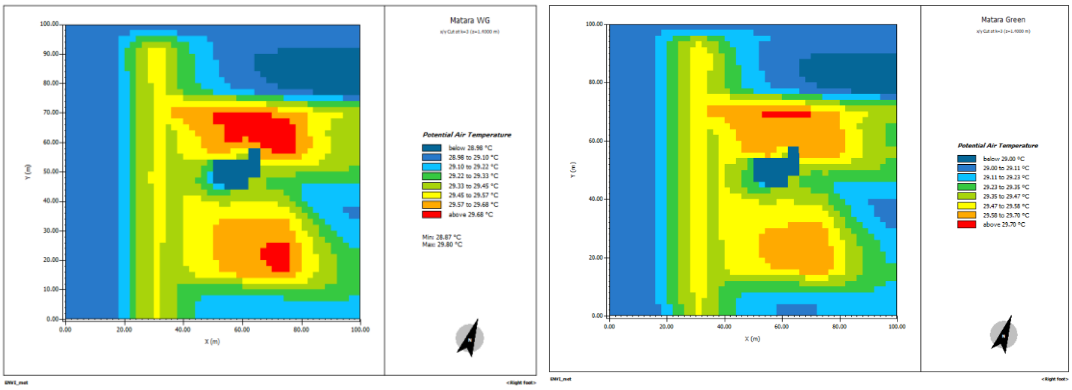


Figure 7.14: Temperature contour map of Matara MC urban context before and after VGS application

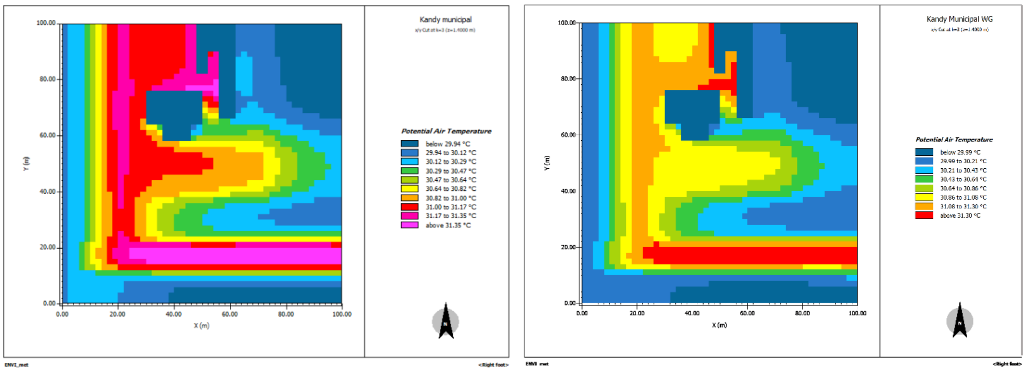


Figure 7.15: Temperature contour map of Kandy MC urban context before and after VGS application

As Theeuwes (2017) highlights addition of 10% vegetation has the potential of temperature reduction in outdoor urban contexts. Above simulated contexts were located in city centers with higher population density due to the functional aspects. Therefore, the CO_2 emission, air pollutants from automobiles and human activities has a direct impact on air temperature increase (Bousse, 2009) creating thermal discomfort in the context (Nuruzzaman, 2015). In such situation, the benefit of implementing vertical greenery in the urban contexts is vital in importance.

7.3.4 Thermal performance in macro urban context

The simulation study was conducted using the Envi-met 4.4 software to identify the possible temperature reduction in urban contexts with the integration of vertical greening. A highly urbanised area of Wellawatta of Colombo metropolitan was selected as the base case. Then the same area was simulated with introducing vertical greenery to the vertical building surfaces of the selected area (Figure 7.16).

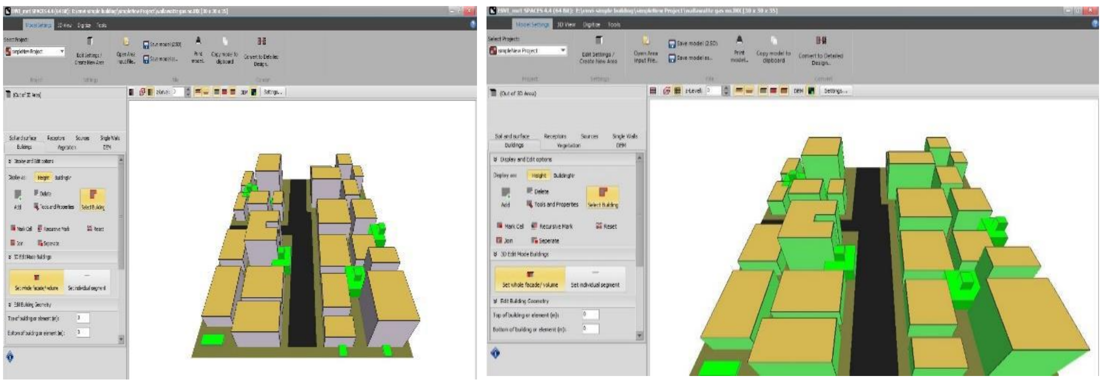


Figure 7.16: Simulated urban context with and without vertical greenery

Initially the base case scenario was modelled and calibrated to identify the compatibility of the simulation. Validation was done comparing the simulated outdoor temperature and the manual temperature measurement data.

Results of the simulation study of thermal performance in macro urban context

The resultant outdoor temperature of the selected Wallawatte urban area signified that by introducing 100% vertical greenery to the building vertical surfaces outdoor air temperature can be reduced.

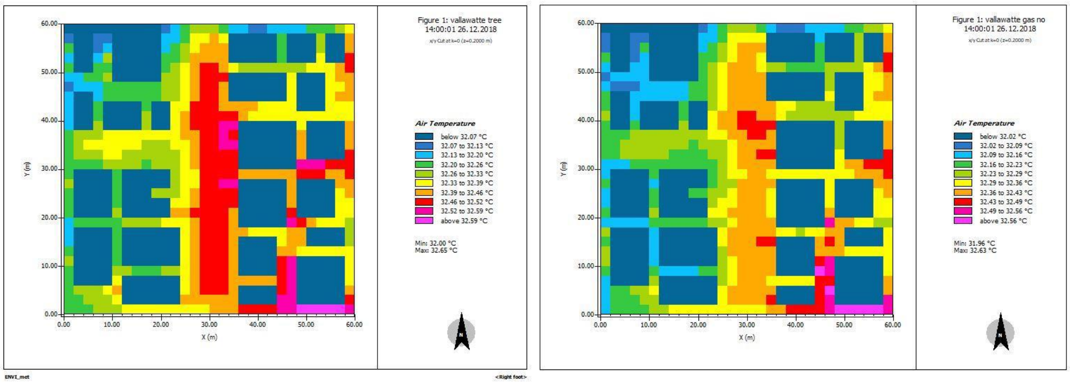


Figure 7.17: Temperature contour map of the urban context with and without vertical greenery

As shown in the Figure 7.17 in which the peak temperature contour map of the simulated Wellawatta area is obtained by using Envi-met LEONARDO with vertical greenery and without vertical greenery signifies that when vertical greenery is integrated intensity of outdoor air temperature is reduced throughout the area. When the outdoor air temperature variation for 24 hours was compared in each situation reduction of temperature was visible for each hour (Figure7.17). The resultant peak outdoor temperature without vertical greenery was 28.97^{o}C whereas with vertical greenery the peak outdoor air temperature was 27.66^{o}C. Thus, the peak outdoor air temperature reduction is 1.29^{o}C when integrating vertical greenery which is a highly positive outcome (Figure 7.18). This signifies the capability of vertical greening in tropical context to reduce the urban outdoor temperature offering the possibility of negating the current urban issue of rising urban temperature.

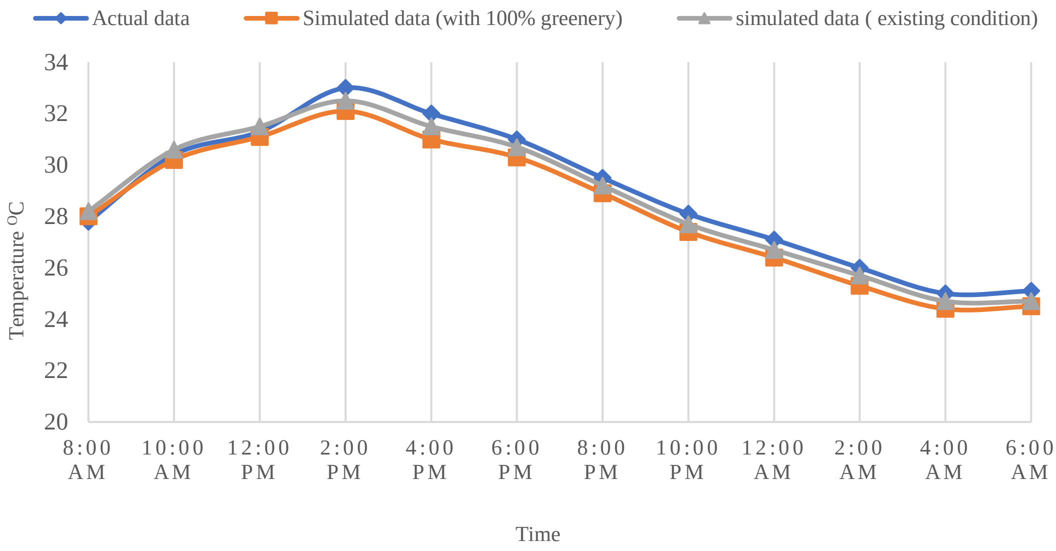


Figure 7.18: Urban air temperature behavior in macro urban contexts (with and without vertical greenery)

Since vertical greening can override the emissivity and the albedo of the typical envelop materials and due to the potential evaporative cooling, vertical greenery can help in reducing the outdoor air temperature in different heights in vertical plain. Combining vertical greenery with other solutions to overcome global warming and high urban temperature will surely be a greater solution while enhancing the comfort in terms of physical, visual, and psychological comfort aspects.

In present the resultant temperature variation which reaches up to 8^{o}C between urban areas and rural areas due to urban heat island effect is one of the major concerns for urban planning. the abundant heat which is absorbed, stored and reemitted to the urban environment by the building materials together with the anthropogenic heat produced by vehicles and power plant are the major contributors of this UHI effect. Thus, urban design interventions must aim at negating this phenomenon. As Tilley et al., (2014) too highlights, VGS provide shading to the surface of a structure while cooling the surrounding due to evapotranspiration. Further, the study has predicted a maximum of 8.4^{o}C in canyon temperature with green roof and green wall integration. The study by Wong et al., (2009) signifies VGS directly influence in reducing mean radiant temperature and air temperature through a simulation study done using a hypothetical building with different green cover. Further evidence from research studies done in Singapore (Tan et al., 2010a) using an experimental set up and the study on outdoor thermal comfort (Tan et al., 2014) validates the above findings. Alexandri & Jones (2008) states roof greening and vertical greening together can decrease the canyon air temperature which reaches to an average day time air temperature reduction of 9.1^{o}C. A similar study done in local context to evaluate the potential of green roofs and green wall to mitigate UHI effect has revealed the combined effect can help in reducing urban temperature by 1.86^{o}C (Herath et al., 2018).

7.4 Long term cost effectiveness of the proposed VGS

With identifying the aesthetical, environmental and social benefits of vertical greening adaptations to buildings, use of VGS as an alternative façade option has also increased. Though number of studies has been carried out in identifying these various benefits a very few has been conducted to analyze the cost benefits related to the application of vertical greening: specially in local context where the VGS application is still at an initial stage. Similar to many other green/sustainable building envelop solutions, the vertical greening systems are identified with high installation and maintenance costs. From the identified numerous environmental and social benefits some can be quantified in economic terms. The main aim of the research is to develop a cost effective, sustainable and ecofriendly double skin green wall that can enhance the energy efficiency and thermal performance of buildings. This chapter focus on evaluating the long-term cost effectiveness of the proposed VGS by identifying the long-term energy saving and cost saving potential both in private and social aspects compared to the initial installation and maintenance cost.

7.4.1 Techniques of Life Cycle Costing evaluation

In addressing the sustainable development goals, Life Cycle Costing (LCC) becomes essential to evaluate the economical and long-term benefits (Ingrao et al., 2018). LCC is defined as the total cost of a specific item throughout its lifetime inclusive of planning, design, acquisition, operations, maintenance and disposal minus any residual value (Schau at al., 2011). According to Emmanuel (2004b) simple pay back method, net present value and Internal rate of return are the most common LCC techniques among the existing methods. From these three methods, net present value is the most common method used in construction sector.

7.4.2 Cost calculation of vertical greening systems

Life cycle cost of buildings is calculated based on the total costs related with construction, operation and maintenance and demolition (Fuller,2016). However, with the evolvement of urban greening concepts cost associated with green roofs and VGS systems too are now being considered. Here, similar to buildings the LCC of VGS too is considered under three stages namely initial, maintenance and disposal (Perini & Rosasco, 2013). In the study done by Huang et al., (2019) cost effectiveness of VGS systems has been argued on how to properly evaluate the life cycle costing of VGS, what are the LCC benchmarks for different VGS systems and finally what are the key factors that determines the cost of VGS. A comprehensive LCC analysis has been conducted to identify the costs involved in VGS as well as the viability of VGS in terms of the associated costs. In analyzing the cost effectiveness of vertical greening personal benefits and social benefits are considered (Perini & Rosasco, 2013). Net present value, internal rate of return and pay back method are the indicators that are used in evaluating the economic sustainability of the vertical greening applications.

7.4.3 Approaches in evaluating cost effectiveness in VGS

Identifying the benefits of implementing vertical greenery in creating sustainable and resilient cities, governmental level initiatives has been taken in international context. Best example is Singapore where various initiatives are already implemented (Ministry of the Environment and Water Resources [MEWR],2014) with the aim of achieving $2Km^2$ of vertical greenery by 2030. Provision of incentives to exemptions from gross floor area limitations, providing bonuses as well as subsides for cost of vertical greenery installations, allotting marks for vertical greenery in green rating systems, recognizing and certifying under landscape excellence framework assessment are some of such initiatives (Urban Redevelopment Authority [URA],2014; National parks board [NParks],2017; Building Construction Authority [BCA],2016). However, even with such encouragement by 2016 Singapore has achieved about $0.805Km^2$ of vertical greenery which is the size of 262 school fields (Huang et al.,2019). Similar to the survey analysis received in local context a survey done in international context too has proven that public perception on installation and maintenance cost of VGS has impeded the adaptation of VGS (Wong, Tang et al., 2010c). According to Perini et al., (2011) costs incur in each stage for each component of the vertical greening system inclusive of one time or recurring costs are considered in structuring LCC for vertical greening. While the supporting structure, plants used and irrigation system are identified as common costs for different VGS (Wong et al., 2009) costs for components such panels, pots, growing media and drainage which differ based on VGS vary accordingly (Ottele et al., 2011). Further discounts, inflation rate, plant selection and life span of greenery system etc. can influence the LCC of the VGS (Fuller, 2016).

7.4.4 Findings related to cost effectiveness of VGS in international context

Energy saving potential of VGS and the property value increment (Des Roieres et al, 2002) are considered significant economic benefits of VGS. This has been proven in several studies done in different contexts (Gao & Asami, 2007). Energy saving potential in terms of summer cooling and winter heating (Mazzali et al., 2012; Alexandri & Jones,2008; Mc Pherson et al., 1998; Krusche et al., 1982) are identified as the main quantifiable economic benefits whereas extra benefits such as protection to building envelop, increased durability of plaster and etc. too are identified as cost saving potentials of vertical greening. However, faulty installation and improper maintenance of VGS may turn against this protection and durability increment of building façade elements. Depending on the factors such as location, type of construction, plant selection, the installation and maintenance costs of a VGS may tend to vary. In the context of green infrastructure vertical greening represents a new dimension. Plants, growth medium, irrigation and the support system are the basic component of any VGS available.

From the four types of VGS; direct green façade, indirect green façade, indirect green façade combined with planter boxes and living walls, living walls are defined as much more expensive than the other types due to the materials, maintenance and design complexity. As per the research done by Perini et al., (2011) when comparing the initial costs associated with different vertical greenery systems, carrier systems are recorded to be much expensive compared to planter system and support system whereas support system is recorded as the least expensive. However, when considering the collective costs in life cycle perspective costs associated with operation and maintenance too must be considered as they contribute nearly 51%-75% to economic viability of the vertical greening systems (Perini et al.,2011; Perini & Rosasco, 2013).

From the available few studies on VGS maintenance the study by Chew et al., (2016) has focused on identifying the issues related to vertical greening during the maintenance and operational stage. There, several operation and maintenance related issues that can contribute to the overall life cycle costs of the VGS has been identified and listed out. Describing the identified 29 issues related to climatic conditions, materials used in VGS, waterproofing, irrigation and drainage techniques, fabrication, maintenance and plant selection the research highlights that less awareness and user expectations as well as the high costs at initial stages and the operation and maintenance related issues has impeded the adoption of VGS by general public. However apart from the technical guidance no detail has been provided on improving maintenance to cut down the associated costs.

a) Cost benefit analysis of VGS

Cost benefit analysis (CBA) is used to identify the cost effectiveness of different vertical greening systems. CBA has been previously used to quantify the costs and benefits of green roofs. It is argued that even though with the increasing interest on adapting vertical greenery due to various benefits the cost effectiveness is less researched compared to research done on its thermal and environmental benefits (Huang et al., 2019). CBA has been utilized by Perini et al., (2011) to ascertain the economic viability of a green envelop system consisting a green roof and VGS. Perini & Rosasco (2013) in evaluating the cost effectiveness of different VGS types have compared the initial, installation, maintenance and demolition costs against the cost saving from reduced energy consumption, property value enhancement and etc. The CBA was conducted on four types of VGS namely direct green façade, indirect green facades supported by plastic and steel meshes, indirect green facades combined with plastic planter boxes supported by plastic mesh and with steel planter boxes supported by steel mesh and living wall where payback period, net present value and internal rate of return were considered as the factors to determine the cost effectiveness. However, CBA evaluate the net effect between the costs and benefits and is more concerned about time period it takes to pay back the costs (Huang et al., 2019).

b) Life cycle costing analysis of vertical greening systems

Identifying the research gap in evaluating the total cost associated with the VGS taking the different types and life cycle stages in to account, Huang et al., (2019) highlights the lack of detailed cost breakdown analysis of VGS inclusive of uncertain factors that may influence the LCC. Thus, in order to obtain accuracy in cost calculations more detailed life cycle costing analysis (LCCA) has been developed reconfiguring the scope of VGS, activities related and other key factors (Figure 7.19).

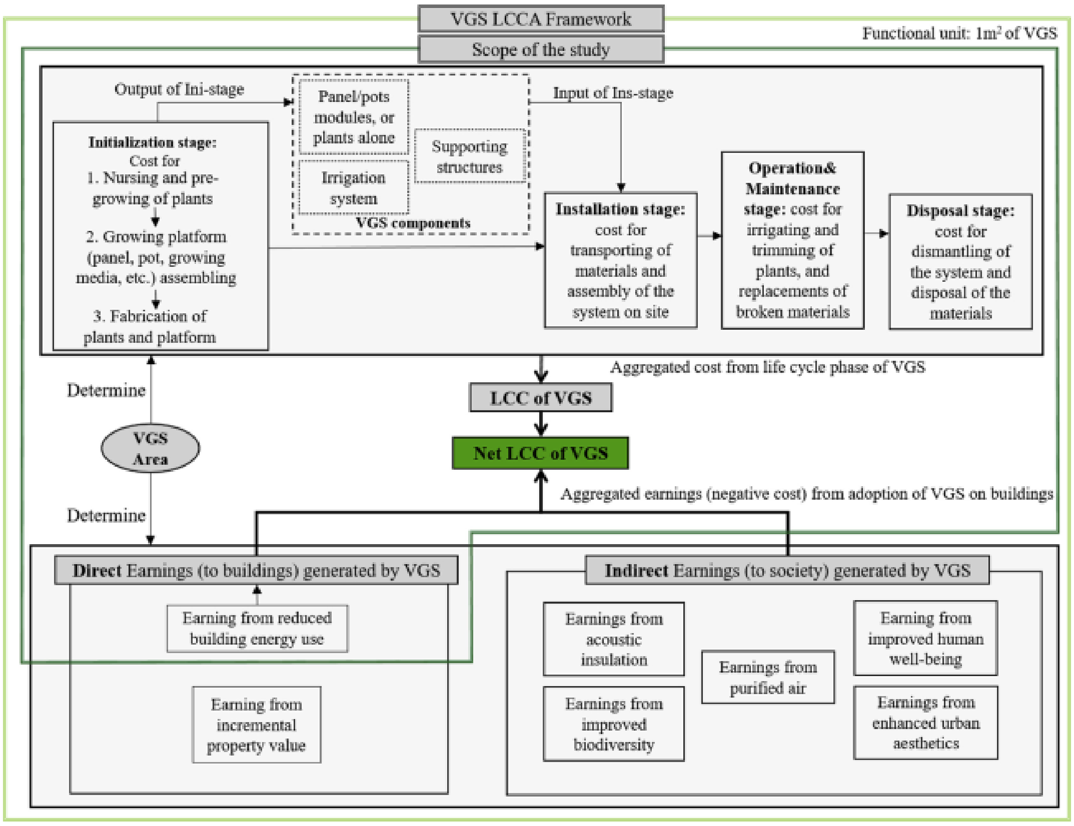


Figure 7.19: LCCA framework for VGS

Source: Huang et al., 2019

It is highlighted that the activities and scopes of different VGS such as requirement of pre-planting and nurturing the planter boxes or modules of living walls must be considered when evaluating the total costs. Moreover, uncertainty analysis too has been considered along with the cost breakdown structure in this proposed LCCA framework. Research evidence suggest such a framework enables a more precise method of decision making on VGS and speed up the cost analysis process (Miah et al., 2017: Jeong et al., 2018). Huang et al., (2019) utilizes LCCA for the evaluation of cost effectiveness arguing that it enables more focused and detailed structural breakdown of the cost components while allowing to explore cost influential components other than the pay-off from main benefits. Until the proposed LCCA framework, the available research evidence properly conducted on cost benefit analysis of VGS was the study done by Perini & Rosasco (2013) in a Mediterranean climate using a virtual case study. Hence the LCCA proposed by Huang et al., (2019) becomes the best framework to adopt in conducting a cost benefit analysis of vertical greening in local context. The proposed framework by Huang et al., (2019) is mainly in two parts; aggregated costs from the life cycle phase and the expected earnings from the VGS.

Considerations for LCCA framework

Compared to the green roof integration and investigations done on costs and benefits of green roofs, the spread of vertical greening as well as research on vertical greening is less as integration of VGS is considered to be expensive. This can be due to the lack of data on costs and benefits of VGS related to maintenance and management and the frequency, longevity of the components and total system (Mahdiyar et al., 2016; Bianchini & Hewage, 2012; Clark et al., 2008).

In the study by Perini & Rosasco (2013) following costs and benefits have been considered.

- Costs;
    - Initial cost (including installation)
    - Maintenance cost
    - Disposal costs
- Economic benefits;
    - Increase of rent income /increase of property value
    - Building envelop longevity
    - Heating/cooling energy demand reduction
- Social economic benefits;
    - Positive environmental effects

c) Economic benefits of vertical greening system

Benefits of vertical greening can be evaluated economically based on the related costs and the range of personal and social benefits they offer. From the first glance the high initial and related maintenance cost impedes the VGS integration of general society. However, once the true personal and social benefits are realized this conception may be overridden. Personal economic benefits of VGS can be defined under reduced energy use during winter for heating as well as in summer for cooling (Mazzali et al., 2012; Dunnet & Kingsbury, 2008; Alexandri & Jones, 2008; Mc Pherson et al., 1998; Krusche et al., 1982). Further the longevity of building components like plaster of facades (Perini & Rosasco, 2013) and reduced cost for façade maintenance like painting and material replacements, façade renovation can be quantified as potential cost saving of VGS. As per Veisten et al., (2012) increased real estate value due to added aesthetic quality and thermal benefits for occupants too are regarded as economic benefits of VGS integration. Reduction of greenhouse gas emission and UHI effect, improvement of air quality, enhancement of indoor and outdoor comfort, improvement of biodiversity are few of the many social benefits of VGS (Collins et al., 2017). Energy saving for heating and cooling façade longevity, aesthetic value, noise attenuation, carbon emission reduction, improving air quality are private benefits and reducing heat island effect, positive effect on hydrology, improving bio diversity and creating habitat are social benefits which are more qualitative than quantitative.

Reduction of indoor air temperature due to solar radiation interception, thermal insulation, cooling inspired by evapotranspiration, wind impact modification by vertical greening integration has been proven in different contexts (Cameron et al., 2015; Hunteretal.,2014; Perezetal.,2011). The research by Susorova et al. (2013) highlights that a façade's thermal resistance can be improved by adding a plant layer to the surface. Perez et al., (2017) highlights the radiation interception capability of leaves by implying the reduction of external surface temperature of the wall by 10.1^{o}C and internal air temperature reduction by 2.5^{o}C. The study done in China by Chen et al., (2013) resulted a maximum 20.8^{o}C external wall surface temperature reduction, 7.7^{o}C internal wall temperature reduction and 1.1^{o}C indoor temperature reduction by a living wall in hot humid climate. Further excess humidity entering to the interior too has been reduced due to the living wall. A similar result of 20^{o}C external surface temperature has been recorded in the research by Mazzali et al. (2013). In Mediterranean climate condition 10.8^{o}C temperature reduction has been recorded (Eumorfopoulou and Kontoleon, 2009). The outdoor air temperature adjacent to vertical greening system can be cooled by approx. 6^{o}C (Davis et al., 2016a).

Energy demand for cooling too is significantly reduced with VGS integration (Meier, 2010). A research by Hasan et al. (2012) has recorded 9.5%-18% cooling energy consumption reduction in a commercial building by utilizing a green facade. A case study conducted in Canada too has recorded a 20% energy saving for cooling due to cooling and shading provided by VGS (Bass and Baskaran, 2001). As per the results obtained by Carlos (2015), 37% heating energy consumption reduction could be achieved by a living wall at north façade. Potential environmental benefits such as increment of greenery in urbanities, output reduction of greenhouse gas emission, mitigation of climate change, improvement of air quality and increment of bio diversity come under the social benefits of vertical greenery.

d) Costs of vertical greening systems

According to available literature cost of installation and costs of maintenance are main costs related to vertical greening systems. Based on the location of the installation, type of selected vertical greening system, plant species and such factors the installation and maintenance costs of VGS vary.

i) Cost of installation

The study done by Perini and Rosasco (2013) evaluated the costs related to four different VGS types in European context. The findings highlighted that the costs related to living walls are higher than other VGS types. Apart from that based on the distance between the installation location and manufacturer decides the transportation costs of VGS which may vary from 6% to 10% of the total costs. At the end of the lifespan of the VGS disposal of the system too incur a significant cost.

ii) Cost of maintenance

Maintenance cost is considered as the main cost of VGS. Vertical greening system, selected plant type, climatic condition of the location determines the cost of maintenance as well as the frequency of pruning and replacement of plants. Research evidence suggests plant replacement can vary between 5%-15% in general (Pe´rez-Urrestarazu et al., 2015; Perini and Rosasco, 2013; Ottele` et al., 2011;) whereas it may reach 50% in some instances (Perez-Urrestarazu et al., 2015). Cost of irrigation too depends on the local climatic condition (Perez-Urrestarazu et al., 2014) as well as material, length and diameter of pipes.

7.4.5 Cost benefit analysis of the proposed vertical greening system

Based on available literature lifespan of VGS can be assumed to be between 30-50 years (Ottele et al., 2011; Perini & Rosasco, 2013; Feng & Hewage, 2014). Therefore, for the cost-effective analysis of the proposed VGS life span is considered as 50 years. The same building simulated for energy consumption evaluation was taken as the case study for the building to evaluate the cost effectiveness of the proposed vertical greening system (Figure 7.20). Considered area of the building for VGS is 3600sq.m for the study.

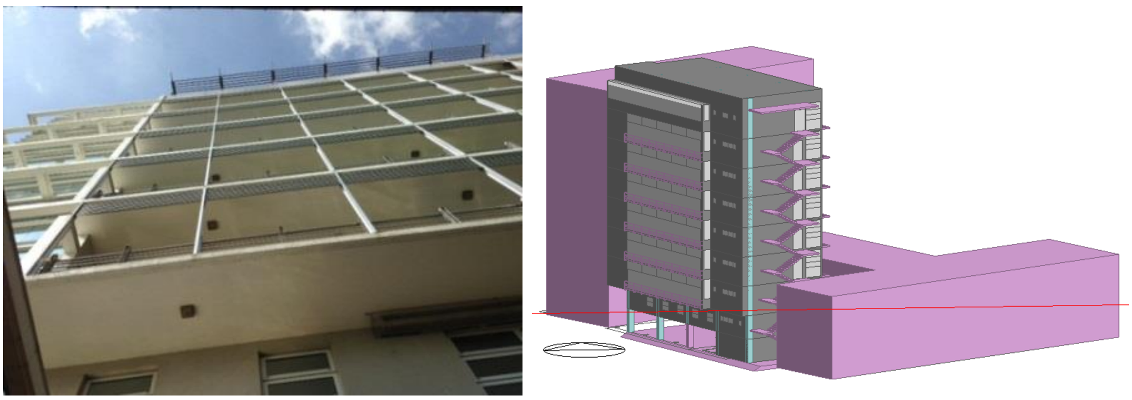


Figure 7.20: Case study for the cost benefit analysis of proposed VGS

According to the literature the costs related to the VGS is given in the below Table 7.2.

Table 7.2: Costs related to the VGS

	Perspective	Category	Cost	Cost Range (Rs ft^2)	Time Frame
Proposed VGS	Private & Social	Initialization & installation	Panels	800	One time
			Installation & Transportation	460	One time
			Plant Species & growth media	102	One time
			Irrigation system	70	One time
			Structure	400	One time
		Maintenance	Pruning & Adjustments (10%)	10.20	Annual
			Irrigation	210	Annual
			Panel replacement (5%)	22.50	Annual
			Plant replacement (10%)	45	Annual
			Pipe replacement (15%)	10.5	Annual
		Disposal	Green Layer disposal	460	One time

The total costs of the stages initialization, installation, operation and maintenance and the disposal collectively results the total life cycle costs of the vertical greening system. When calculating the cost rates manpower was taken by considering the hourly pay for a worker and multiplying it by the work hours related to the VGS. Total cost of the components of the proposed VGS was considered in calculating the material cost rates including the utility and equipment rates, transportation costs which were taken based on available economical options.

Initialization stage consist of acquiring and preparing the different parts required for the VGS. According to literature this is considered as the second most expensive stage of VGS life cycle for any VGS system (Huang et al., 2019). As the study by Huang et al., (2019) highlights, planter systems which is the expensive VGS system of available vertical greening types has the highest initialization cost as well. Frames and panels contribute to a higher percentage of initialization cost in planter systems. Comparing to other modular panel systems the proposed system is designed where plant growth and panel preparation can be easily done without specific expert knowledge. Therefore, costs related to nursing the plants and plants are much less in this system.

Installation cost accounts for the costs related to fixing and installing the VGS. As per the literature for any VGS installation cost is much less in percentage compared to the initialization stage and operation and maintenance stage. Manpower, transportation are the main costs that incur in the installation stage (Ministry of Manpower [MOM], 2016). Operation and maintenance stage is the highest contributor for the life cycle cost of a VGS as it occurs annually throughout the life cycle whereas other stages are one-off costs. Same result has been obtained in the studies conducted by Huang et al., (2019) and Perini & Rosasco (2013). The studies further highlighted that replacement of plants contribute to a significant amount of operation and maintenance costs. The proposed system utilizes a commonly available plant species which is less expensive thereby considerably reducing the plant related cost during the operation and maintenance stage. Other than plants manpower required for operation and maintenance, cost of irrigation, cost of material and equipment that need to be replaced are added as costs of operation and maintenance.

Comparatively disposal stage is considered as the least expensive stage for all available VGS. However, when considering the vertical greening types disposal of modular panel systems may be expensive than other vertical greening types. The labor used for the dismantling of the system accounts for the manpower costs in this stage. Transportation of waste material too is added to the total cost of disposal stage. However, with the durability of the panel material the panels which are in good condition may be reused which is an added benefit of the proposed VGS. Area considered for the VGS installation is 3600sq.ft. Accordingly, the total costs of the proposed VGS for the considered time period is given in the below Table 7.3.

Table 7.3: Total costs related to the VGS

	Perspective	Category	Cost	Cost Range (Rs)
Proposed VGS	Private & Social	Initial	Panels	2,880,000
			Installation & Transportation	1,656,000
			Plant Species & growth media	367,200
			Irrigation system	252,000
			Structure	1,440,000
		Maintenance	Pruning & Adjustments (10%)	1,836,000
			Irrigation	37,800,000
			Panel replacement (5%)	4,050,000
			Plant replacement (10%)	8,100,000
			Pipe replacement (15%)	1,890,000
		Disposal	Green Layer disposal	1,656,000
Total Cost				**61,927,200**

Apart from the costs related to VGS the potential savings of integrating vertical greenery is directly related to the possible energy saving achieved by vertical greening application. Further the saving of façade maintenance cost too is considered as a quantifiable saving potential of the proposed VGS. The saving of the VGS for 50 years are calculated as given in the Table 7.4 and Table 7.5.

Table 7.4: Saving potential for 50 years

	Perspective	Category	Saving	Cost (RS)	Time Frame
Proposed VGS	Private	Operation	Energy	983,601	Annual
		Maintenance	Façade painting	1,116,000	Once in three years

Table 7.5: Total saving for 50 years

	Perspective	Category	Cost	Cost Range
Proposed VGS	Private	Operation	Energy	49,180,050
		Maintenance	Façade painting	18,972,000
Total Saving				**68,152,050**

When considering the total costs and the total saving of the proposed VGS the total Cost saving for 50 years is calculated as 6,224,850 rupees (Figure 7.21). However, this saving is calculated by only considering the directly quantifiable benefits of vertical greening system which are energy saving and façade maintenance saving. Majority of the VGS related benefits can be subjective which depends on user perception thus, may vary based on different contexts (Huang et al., 2019).

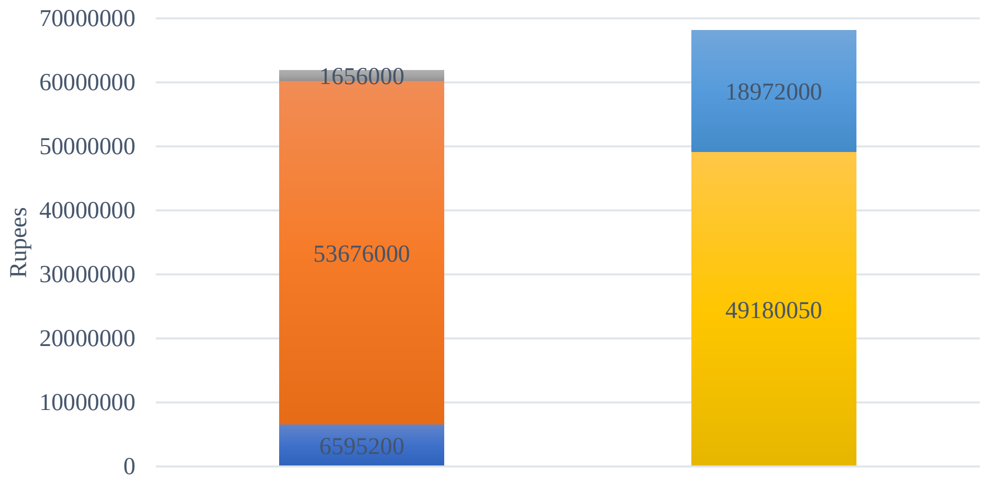


Figure 7.21: Comparison of costs and savings of the proposed VGS for 50 years

It should be noted that the findings of Jayakody (2020) highlighted that long-term savings of living walls in local context were not achievable due to high costs in existing vertical greening systems when considering the life time. In contrary, the proposed vertical greening system proves to be effective in cost saving in long term application. According to Huang et al., (2019) the energy saving potential of VGS is the most significant which can be considered in balancing the costs related to vertical greening. In some countries' regulations have been implied to reduce the tax of buildings that integrate VGS which is a personal benefit for building owners. However, on the other hand this is considered a social cost as it reduces the tax revenue. For instance, in Italy 65% of installation and design costs of VGS had been reduced from tax, based on the improved performance of insulation of building. Thus, government tax regulations, property value increment too should be considered once the systems are implemented.

Number of researches finding conducted in different contexts have validated that VGS can directly contribute to reduce the energy consumption of buildings. Research conducted in Singapore has provide evidence that integration of vertical greenery helps in reducing surface temperatures of buildings as well as mean radiant and air temperature which helps in reducing cooling loads. Similar results were obtained in local context as well (Rupasinghe & Halwatura, 2020). Apart from the energy saving potentials VGS are beneficial vary in a larger range including environmental, social and aesthetical benefits. Noise attenuation, air quality improvement is proven as environmental benefits (Wong, Tan et al., 2010b; Currie & Bass, 2008) whereas improved work productivity, lower blood pressure levels, speed recovery of patient are proven as social benefits of VGS related to health and wellbeing of people (Dahlkvist et al., 2016; Khan et al., 2016; Bringslimark et al., 2007; Stigsdotter & Grahn, 2004). In terms of aesthetic benefits of VGS influencing visual interests, increase of property value, beautification of facades is highlighted (Wang et al, 2016) whereas Baker et al., (2014) states VGS can contribute as public art to improve the visual interest which can also influence visual relief in crowded urban contexts. On the other hand, Chiang (2009) highlights that since the VGS acts as a protective layer to the wall surface the service life of materials becomes longer and reduce the costs of repainting, replacing façade material etc. which reduces the maintenance related costs.

7.5 Chapter summery

Benefit of implementing vertical greenery in obtaining thermal benefits have been discussed and verified in available literature. The effect of VGS on building surfaces and thermal properties in reducing the internal temperature by reducing the wall surface temperature and mean radiant temperature which directly help in reducing the energy consumption for cooling surfaces is a major benefit of VGS. On the other hand, benefit of vertical greenery in terms of reducing the outdoor air temperature which can be used as a direct method to mitigate the rise of urban air temperature too is a significant benefit of vertical greening to create comfortable urban environments. Both these benefits are highly important in addressing to the current global environmental issues in both building scale and urban scale. Therefore, evaluating the potential thermal benefits of the proposed modular panel vertical greening system was identified as vital of importance.

This chapter was based on the thermal benefit evaluation of the proposed VGS system. To achieve this simulation studies were conducted in both building scale and urban scale. Two simulation software namely; design builder and Envi-met were utilized for the simulation studies to test the performance of the proposed VGS. Results revealed that the proposed modular panel vertical greening system has a significant potential in reducing the internal air temperature and cooling load consumption in buildings directly influencing energy saving of building during the building operational stage. This can also help in creating thermally comfortable indoor environments for the building occupants as well. Further, the proposed VGS proved to be beneficial in reducing the urban air temperature in local context which is vital in addressing the high urban temperature related issues whereas creating comfortable and greener urbanities in local context.

Further, the chapter focused on analyzing the cost benefit of the proposed vertical greening in long term application. Through the questionnaire survey conducted in the earliest stage of the study it was evident that vertical greening is considered to be an expensive architectural integration due to the lack of data and investigation on their economic benefits against the installation and maintenance costs. Therefore, analyzing the cost effectiveness of the proposed vertical greening system was identified as important.

Comparatively modular panel vertical greening systems are high in costs than other vertical greening types. However as proven in earlier chapters, despite the higher costs of initiation, maintenance, panel replacement and etc. the thermal benefit and the aesthetic appeal of modular panel vertical greening system is high. The total saving of the proposed VGS is calculated only based on the two quantifiable benefits which are the energy saving and façade maintenance saving. Apart from these there are numerous private and social benefits of vertical greening. Therefore, with the potential private & social benefits related to improved bio diversity, human health & well-being, enhanced urban aesthetics, air purification, acoustic insulation, UHI mitigation and etc. the cost effectiveness of VGS become more significant. Further the real state value increment and tax release potential with the integration of the vertical greening system too adds a considerable saving and a value on the proposed VGS.

8. CONCLUSION AND RECOMMENDATIONS

8.1 Conclusions

In tropics, heat transfer into the building interior through the building facade is higher thereby making internal temperature also high. Thus, the energy consumed for air-conditioning too is high. Building facade related design interventions has much potential in terms of making buildings sustainable as building envelop is the main component which interacts with the outdoor environment. Research evidence suggests design interventions for building facade can greatly contribute in reducing the cooling load of a building by moderating the internal air temperature. Further, external double skin facades are more beneficial in terms of thermal regulations inside the buildings.

Urbanisation and high population in urban contexts have directly caused urban environmental issues relating to UHI, air pollution, green depletion and etc. Urban greenery has been identified as the best solution to address these issues as trees acts as natural carbon sinks and provide shading which directly help in cooling the surrounding. However, with the high population densities and densely packed buildings in urban contexts promoting vegetation is an issue. Further, high demand for land and the high land values impedes the greenery promotion and instead promote green depletion. In this context, vertical greenery has been identified as a solution to promote greening in urban contexts since vertical surfaces are abundant in urban contexts.

The research aimed at identifying the potential of utilising vertical greenery as the external skin of a double skin envelop which can be benefited to both the building interior as well as building exterior in terms of thermal regulation in building interiors and urban contexts in local tropical condition. Though the thermal benefit of vertical greening has been studied competently in international contexts, vertical greening related studies in local context is very less and the full potential of vertical greening has not been established. First step of the research sequence was to identify the potential of introducing vertical greenery to the local context as a sustainable building intervention.

Three separate questionnaire surveys were conducted to identify the perception on vertical greening of the general public, building occupants and building designers. Through the response of the general public it was evident that majority of the public are positive in adapting vertical greenery to their private buildings. Aesthetical appeal that is obtained through vertical greenery is the main advantage perceived by the general public whereas the thermal benefit, acoustic insulation, air purification has been identified by a minority. However, the lack of knowledge and information on the installation, maintenance and costs has impeded the adaptation of vertical greening to domestic level.

Survey conducted for the occupants who are occupying the buildings that are integrated with vertical greenery resulted that the benefit of vertical greenery in terms of influencing physical comfort, visual comfort and psychological comfort has been perceived by the occupants. This confirms that vertical greenery can be used as a remedy for sick building syndrome while promoting efficiency of the occupants as well.

Designer perception of vertical greening questionnaire survey too signified that majority of the designers are positive in adapting vertical greening concepts in designs as a sustainable approach. In general cost related to VGS, maintenance related issues, lack of proper knowledge on VGS were highlighted as the main concerns related to VGS application in all three questionnaire surveys despite the willingness of the respondents to adaptation of VGS to local context.

Even though vertical greening is being adapted in international context in a rapid pace, vertical greening integration in local context is still at an initial level. Therefore, as the next step of the research existing situation of vertical greening was investigated to identify the existing vertical greening types, plants used, maintenance systems and the thermal benefit of the existing systems in local situation. Through field studies three vertical greening systems: direct facades, indirect facades and living walls were identified in the local context. From the three types indirect green walls were much popular due to the easy installation and maintenance.

Twenty case studies were identified for basic observation study from which nine cases were selected for detailed analysis taking three case studies to represent each existing VGS types. All three vertical greening types signified to be beneficial in thermal regulation. However, in terms of thermal benefit of the three types, living wall systems were identified to be more beneficial which recorded a maximum temperature reduction of 10.15^{o}C at the façade shaded by the living wall and a reduction of 2.21^{o}C in internal air temperature. When considering the average relative humidity and CO_2 profile, an increment of RH by 1.6% - 1.8% and an average CO_2 reduction by 0.63% were recorded at vertical greening systems compared to bare wall control in local tropical climatic condition.

Since the main objective of the research was to develop a modular panel green wall system that can be installed as the external skin of the double skin facade which is affordable, easy to handle and maintain, the field studies were conducted to materialise the designed modular panel vertical green wall system in actual scale. Initial field studies were conducted to develop the individual panels which were then assembled as the green wall system. From the selected twelve-plant species investigated, five plant species namely *Rhoeo spathacea, Axonopus compressus, Portulaca grandiflora, Ophiopogon japonicas and Elusine indica* were shortlisted through field investigation of plant selection for the proposed vertical greening system.

Basic thermal performance and survival analysis of the five species resulted in selecting the two species *Rhoeo spathacea* and *Axonopus compressus* as the best two plant species for the proposed VGS. In-depth field analysis of the selected two species resulted in finalising *Axonopus compressus* as the plant species for the proposed modular panel vertical greening system which recorded a maximum 10.08^{o}C external wall surface temperature reduction and 3.15^{o}C internal surface temperature reduction.

Based on the field observations and literature, the growth media was decided to be a mix of coir, sand, compost and soil where coir was selected to be the main component. Laboratory test to obtain the compaction curve and the permeability of the media resulted in finalizing the growth media mix to be 1:1/2:1/2: 1/4 coir: sand: compost: soil ratio which displayed the best compaction and the permeability for the plant growth in the proposed vertical greening system.

Size of the modular panel for the walling system was finalized as 600mm (width) x 900mm (height) which enables easy handling and the material was selected as fiber due to strength and durability. The size and the materiel selection allowed easy installation and minimum technical support while allowing easy replacement of panels when required. Through permeant wilting point and field capacity tests the irrigation sequence and the water requirement for the panels were identified. When installed to be an external leaf of a double skin building facade, the walling system recorded a temperature reduction of 17.26^{o}C, 7.89^{o}Cand 2.89^{o}C in external wall surface, internal wall surface and the internal air temperature respectively.

Simulation studies which were conducted to further evaluate the potential benefits of the developed VGS in building scale and urban scale resulted significant indoor air temperature reduction, cooling load reduction and urban air temperature reduction. In building scale, the resulted indoor air temperature behaviour with VGS integration was lower than that of existing situation with no VGS and with the addition of vertical greening to each façade the indoor air temperature reduction recorded to be higher indicating more green cover can influence more cooling inside the buildings.

A potential indoor air temperature reduction of 2.4^{o}C was demonstrated under non-air-conditioned mode of operation highlighting the achievable passive cooling by integrating the developed VGS. The potential energy saving due to VGS too was indicated to be considerably high where 46.117% of energy consumption reduction under air-conditioned mode was recorded in a simulated case study.

In terms of urban contexts, the developed VGS proved to be much beneficial in reducing urban outdoor air temperature despite the urban context. Potential urban air temperature reduction in micro scale which considered only the immediate surrounding of the selected building was found to be 2.03^{o}C-3.29^{o}C whereas with 100% vertical greening application in macro scale in a highly urbanized area the urban air temperature reduction was resulted to be 1.29^{o}C.

When integrating the developed modular panel green wall, the quantifiable long-term benefits are achievable in terms of savings from energy consumption and façade maintenance. However, the social and private benefits in terms of sustainability, mental and physical health, property value, promotion of bio diversity, reduction of pollution and numerous un-quantifiable benefits achievable through the developed vertical greening system adds more value in higher magnitude. Therefore, the developed vertical system is beneficial both building scale to reduce the energy consumption and occupant comfort as well as in urban context to mitigate UHI and global warming while promoting sustainable and healthy urban environments.

8.2 Recommendations

- In Sri Lanka general public, building occupants as well the building designers are willing to accept the vertical greening as a sustainable approach for buildings. Therefore, introducing and integrating vertical greening in local context should be achieved by increasing awareness and further research on VGS applications.
- From the available three vertical greening types, living wall systems are more beneficial in terms of the thermal modification. Therefore, adopting living wall system to the proposed VGS to be integrated as the external skin of a double skin facade is beneficial for the local context.
- *Axonopus compressus* is the most suitable plant species for the proposed modular panel vertical greening system due to the availability, survival ability and thermal performance.
- Growth media mix 1:1/2:1/2: 1/4 coir: sand: compost: soil ratio is the best ratio with optimum compaction and the permeability for the plant growth for the proposed VGS.
- 600mm (wide) x 900mm (height) size modular panel enables easy handling, maintenance of individual panels and make provisions for openings in the total living wall system.
- Providing 2.27L of water once in eight days for seven minutes for an individual panel through the designed drip irrigation setup under normal weather condition is required to maintain the water requirement of the panels.
- As depicted by the building scale simulation studies, developed VGS is beneficial in reducing the building facades' surface temperature, internal air temperature and energy consumption for cooling in local context when applied as the external skin of a double skin facade. Therefore, the VGS can be applied as a passive design intervention to make buildings energy efficient and sustainable in local context.
- As per the urban scale simulation studies, the developed VGS when integrated to building facades is beneficial in reducing the outdoor urban air temperature as well. Therefore, this VGS is a better option to promote sustainable urbanities by negating the UHI effect and temperature rise in local urban contexts while increasing urban greenery.

- Quantifiable long-term benefits are achievable through the developed VGS in terms of savings from energy consumption and façade maintenance and numerous un-quantifiable benefits related to sustainability and health. Therefore, implementing tax release procedures in local context would help in promoting and encouraging the application of the developed VGS.

8.3 Further studies

The research and the results presented put forward a strong theoretical basis and findings to highlight the applicability of vertical greening as the external skin of double skin facades in tropics. Further study is required to confirm the findings and improve the efficiency and the effectiveness of the developed VGS. Therefore, the study can be further extended in following aspects;

- Structural integrity and optimum installation height of the developed VGS can be further investigated
- Performance, durability and maintenance aspects can be investigated over extended period
- Optimum air gap to be maintained between the two skins of the double skin façade to act as the external air curtain to achieve the best thermal benefit in local context
- Effectiveness of the developed VGS in different urban contexts in actual situation can be investigated
- Potential noise attenuation and air pollution mitigation through the developed VGS can be investigated
- Comparison of thermal benefit in building and urban scale based on the orientation and different height levels of the proposed vertical greening system when integrated as a double skin façade.
- Investigation on alternative materials/recycled materials for the modular panel construction can be investigated
- Possibility of promoting urban farming through the developed system by using different plant species can be investigated

REFERENCE

Abel, E. (1994). Low-energy buildings, *Energy and Buildings*, Vol. 21-3,169-174

Adalberth, K. (2000). *Energy Use and Environmental Impact of New Residential Buildings*. Byggnadsfysik LTH, Lunds Tekniska Högskola.

Adger, W.N., Huq, S., Brown, K., Conway, D., & Hulme, M. (2003). Adaptation to climate change in the developing world. *Progress in Development Studies*, Vol. 3, 179–195. doi:10.1191/1464993403ps060oa

Alexandri, E., & Jones, P. (2008). Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building & Environment*, 43, 480–493. doi: 10.1016/j.buildenv.2006.10.055

Anderson, M. (2016). Embrace the Vertical: Creating Greenwalls. Available at: http://www.newenglandgrows.org/pdfs/ho_Anderson14HandoutFRI.pdf

Asmone, A.., Conejos, S., Chew, M.Y.L., & Piyadasa, R.U. (2016). Urban Green Cover Protocol to Reduce Urban Heat Island in Sri Lanka, in: *International Conference on Countermeasures to Urban Heat Island*. National University of Singapore.

Azkorra, Z., Pérez, G., Coma, J., Cabeza, L.F., Bures, S., Álvaro, J.E., Erkoreka, A., & Urrestarazu, M. (2015). Evaluation of green walls as a passive acoustic insulation system for buildings. *Applied Acoustics*, Vol. 89, 46–56. doi:10.1016/j.ap

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 MalaysiaJapan Model on Technology Partnership: International Proceedings 2013 of Malaysia-Japan Academic Scholar Conference*, pp. 369–376. doi: 10.1007/978-4-431-54439-5_37.

Bakar, N.I.A., Mansor, M., & Harun, N. Z. (2014). Vertical greenery system as public art? Possibilities and challenges in Malaysian urban context. *Procedia-Soc. Behav. Sci*., Vol.153, 230e241

Balaras, C. (1996). Cooling in buildings. In M. Santamouris (Eds), *Passive cooling of buildings* (pp. 1-30). London: James & james.

Barrio, E. P. D. (1998). Analysis of the green roofs cooling potential in buildings, *Energy and Buildings*, Vol. 27, pp. 179-193,0378-7788, doi:10.1016/S0378-7788(97)00029-7

Bass, B., & Baskaran, B. (2001). *Evaluating Rooftop and Vertical Gardens as an Adaptation Strategy for Urban Areas*. Institute for Research and Construction NRCC-46737, Project number A020

Bastidas-Arteaga, E., Schoefs, F., Stewart, M. G., & Wang, X. (2013). Influence of global warming on durability of corroding RC structures: A probabilistic approach. *Engineering Structures*, Vol. 51, 259–266.

Building Construction Authority. (2016). *Green Mark for Non-Residential Buildings* NRB:2015.

Bianchini, F., & Hewage, K. (2012). Probabilistic social cost-benefit analysis for green roofs: A lifecycle approach. *Build. Environ*., Vol. 58, 152e162

Boden, T.A., Andres, R.J., & Marland, G. (2016). *Global, Regional, and National Fossil-Fuel CO_2 Emissions.* Carbon Dioxide Information Analysis Center.

Bousse, Y.S. (2009). Mitigating the urban heat island effect with an intensive green roof during summer in Reading, UK [Unpublished master's theses]. University of Reading.

Bringslimark, T., Hartig, T., & Patil, G.G. (2007). Psychological benefits of indoor plants in workplaces:putting experimental results into context. *Horticultural science*, Vol. 42 (3), 581e587.

Byomkesh, T., Nakagoshi, N., & Dewan, A.M. (2012). Urbanization and green space dynamics in Greater Dhaka, Bangladesh. *Landsc. Ecol. Eng*., Vol. 8, 45–58. doi:10.1007/s11355-010-0147-7

Cameron, R.W.F., Taylor, J., & Emmett, M. (2015). A Hedera green façade - Energy performance and saving under different maritime-temperate, winter weather conditions. *Build. Environ*., Vol. 92, 111–121. doi:10.1016/j.buildenv.2015.04.011

Cantuaria, G. (2000). A comparative study of the thermal performance of vegetation on building surfaces. In: *PLEA: Architecture, City, Environment*. Cambridge, UK: James & James (Science Publishers) Ltd.

Carlos, J.S. (2015). Simulation Assessment of Living Wall Thermal Performance in Winter in the Climate of Portugal. *Building Simulation*. Springer

Charoenkit, S., & Yiemwattana, S. (2016). Living walls and their contribution to improved thermal comfort and carbon emission reduction: A review. *Build. Environ.,* https://doi.org/10.1016/j.buildenv.2016.05.031

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

Chew, M.Y., & Conejos, S. (2016). Developing a green maintainability framework for green walls in Singapore. *Structural Survey*., Vol. 34 (4/5), 379e406

Chiang, K. (2009). *Vertical Greenery for the Tropics*. National Parks Board.

Chiesura, A. (2004). The role of urban parks for the sustainable city. *Landsc. Urban Plan.*, Vol.68, pp. 129–138. doi:10.1016/j.landurbplan.2003.08.003

Clark, C., Adriaens, P., &Talbot, F.B. (2008). Green roof valuation: a probabilistic economic analysis of environmental benefits. *Environ. Sci. Technol.,* Vol. 42

Clark C, Talbot B, Bulkley J, & Adriaens, P. (2005). Optimization of green roofs for air pollution mitigation. In: *Proceedings of the third North American green roof conference: greening rooftops for sustainable communities*, Washington, DC, Toronto, 4e6 May. The Cardinal Group; 2005. p. 482e97

Cohen, B. (2006). Urbanization in developing countries: Current trends, future projections, and key challenges for sustainability. *Technol. Soc*., Vol. 28, 63–80. doi: 10.1016/j.techsoc.2005.10.005

Collins, R., Schaafsma, M. & Hudson, M.D. (2017). The value of green walls to urban biodiversity. *Land Use Policy.* 114123

Currie, B.A., & Bass, B. (2008). Estimates of air pollution mitigation with green plants and green roofs using the UFORE model. *Urban Ecosyst*., Vol.11 (4), 409e422.

Dahlkvist, E., Hartig, T., Nilsson, A., Högberg, H., Skovdahl, K., & Engström, M. (2016). Garden greenery and the health of older people in residential care facilities: a multi-level cross-sectional study. *Journal of advanced nursing*, 72(9), 2065–2076. https://doi.org/10.1111/jan.12968

Daly, H.E., & Cobb, J.B. (1994). *For the Common Good: Redirecting the Economy toward Community, the Environment, and a Sustainable Future*. 2nd Edition, Beacon Press, Boston.

Davis, M.J.M., Ramirez, F., & Pe´rez, M.E. (2016a). More than just a Green Facade: Vertical gardens as active air conditioning units. *Proc. Eng*., Vol.145, 12501257.

Davis, M.J.M., Tenpierik, M.J., Ramı ´rez, F.R., & Pe´rez, M.E. (2016b). More than just a green facade: The sound absorption properties of a vertical garden with and without plants. *Build. Environ.*

Dayaratne, R. (2010). Moderating Urbanization and Managing Growth: How Can Colombo Prevent the Emerging Chaos? UNU-WIDER, Helsinki, Finland. pp.18. ISBN 978-92-9230-302-0 [WIDER Working Paper No. 2010/64]

DeFries, R.S., Rudel, T., Uriarte, M., & Hansen, M. (2010). Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nat. Geosci*., Vol. 3, 178–181. doi:10.1038/ngeo756

Des Rosiers, F., Thériault, M., Kestens, Y., & Villeneuve, P. (2002). Landscaping and house values: an empirical investigation. *Journal of Real Estate Research*, Vol. 23:139e61

Di, H., & Wang, D. (1999). Cooling Effect of Ivy on a Wall. *Experimental Heat Transfer*. Vol. 12(3): (pp. 235-245)

Diprose, P.R., & Robertson, G. (1994). *Towards a fourth skin? Sustainability and double envelope buildings, in WREC*. Retrieved February from ScienceDirect.

Dunnett, N., & Kingsbury, N. (2008). Planting Green Roofs and Living Walls. Timber Press: Portland

Economist Intelligence Unit. (2017). *The global livability index 2017:* A free overview. https://imco.org.mx/wp-content/uploads/2017/08/Liveability-Ranking-Free-Summary-Report-August-2017.pdf

Emmanuel, R. (2004b). Estimating the environmental suitability of wall materials: preliminary results from Sri Lanka. *Building and Environment*, Vol. *39*(10), pp. 1253–1261. https://doi.org/10.1016/j.buildenv.2004.02.012

Environmental Protection Agency. (EPA). (2008) *EPA's 2008 Report on the Environment*. National Center for Environmental Assessment, Washington, DC; EPA/600/R-07/045F. Available from the National Technical Information Service, Springfield, VA, and online at http://www.epa.gov/roe.

Environmental Protection Agency. (2008). *Reducing Urban Heat Islands: Compendium of strategies.* [online]

Eumorfopoulou, E.A., & Kontoleon, K.J. (2009). Experimental approach to the contribution of plant-covered walls to the thermal behaviour of building envelopes. *Building and Environment*, *44*(5),1024-1038.

Feng, H., & Hewage, K. (2014). Lifecycle assessment of living walls: air purification and energy performance. *J. Clean. Prod.*, Vol. 69, 91e99

Fitch, J. (1972). *American Building 2: the environmental forces that shape it.* Boston: Hougton Mifflin.

Fuller, S. (2016). Life-cycle cost analysis (LCCA). from. https://www.wbdg.org/ resources/life-cycle-cost-analysis-lcca

Gao, X., & Asami, Y. (2007). Effect of urban landscape on land price in two Japanese cities. *Landscape and Urban Planning*.

Garnaut, R. (2008). Will climate change bring an end to the platinum age? *Asian–Pacific Economic Literature*, Vol. 22, Issue 1, pp 1-14

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

Golden, J.S. (2004). The built environment induced urban heat island effect in rapidly urbanizing arid regions – A sustainable urban engineering complexity. *Environ. Sci*., Vol.1, pp. 321–349. doi:10.1080/15693430412331291698

Gossauer, E., & Wagner, A. (2008). Occupant satisfaction at workplaces – a field study in office buildings. *Air Cond. Low Carbon Cool. Challenge*, pp. 27–29.

Gratia, E., & De Herde, A. (2004b). Natural ventilation in a double-skin façade. *Energy and Buildings*, Vol. 36: 137–146

Gratia, E., & De Herde, A. (2004a). Is day natural ventilation still possible in the office buildings with a double-skin façade? *Building and Environment,* Vol. 39: 399–409.

Gusson, C.D., & Duarte, D.H. (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 Engineering*, Vol. 169, 2-10.

Halwatura, R.U & Jayasinghe, M.T.R (2009). Influence of insulated roof slabs on air-conditioned spaces in tropical climatic conditions-A life cycle cost approach, *Energy and Buildings,* Vol. 41, 678–686.

Halwatura, R. U., & Jayasinghe, M. T. R. (2008). Thermal performance of insulated roof slabs in tropical climates. *Energy and Buildings*, Vol. 40(7), pp.1153–1160.

Halwatura, R.U. & Jayasinghe, M.T.R. (2007), Strategies for improved micro-climates in high-density residential developments in tropical climates, *Energy for Sustainable Development*, Vol. XI No. 4 (44-55).

Han, L., Zhou, W., Li, W., & Li, L. (2014). Impact of urbanization level on urban air quality: A case of fine particles (PM2.5) in Chinese cities. *Environ. Pollut.*, Vol. 194, 163–170. doi:10.1016/j.envpol.2014.07.022

Hasan, M. M., Karim, A., Brown, R., Perkins, M., & Joyce, D. (2012). Estimation of energy saving of commercial building by living wall and green facade in sub-tropical climate of Australia. In *Proceedings of the 7th International Green Energy Conference and the 1st DNL Conference on Clean Energy (IGEC-DCCE)* (pp. 672-686). Dalian Institute of Chemical Physics (DICP)-Chinese Academy of Sciences (CAS).

Haase, M., Silva, F. M., & Amato, A. (2009). Simulation of ventilated facades in hot and humid climates. *Energy and Buildings*, 361-373.

Henderson, V. (2002). *Urbanization in Developing Countries*. World Bank Res. Obs. 17, 89–112. doi:10.2307/3986401

Hearth, H. M. P. I., Jayasinghe, G.Y., & Halwatura, R.U. (2016). *A green model to mitigate microclimatic changes in urban areas using Envi-met software case study in colombo city as an urban heat island adaptation strategy* [Unpublished dissertation]. University of Ruhuna.

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 For. Urban Green*. Elsevier Vol. 29, pp. 212–222. https://doi.org/10.1016/j.ufug.2017.11.013.

Herath, H.M.P.I.K., Halwatura, R.U. & Jayasinghe, G.Y. (2018). Evaluation of green infrastructure effects on tropical Sri Lankan urban context as an urban heat island adaptation strategy. *Urban Forestry & Urban Greening*, Vol. 29, pp.212-222.

Herath, H.M.P.I.K., Halwatura, R.U. & Jayasinghe, G.Y. (2018). Modeling a tropical urban context with green walls and green roofs as an urban heat island adaptation strategy. *Procedia engineering*, Vol. 212, pp.691-698.

Hinkel, J., Nicholls, R. J., Tol, R. S. J., Wang, Z. B., Hamilton, J. M., Boot, G., & Klein, R. J. T. (2013). A global analysis of erosion of sandy beaches and sea-level rise: An application of DIVA. *Global and Planetary Change*,111, pp. 150–158.

Hiraishi,T., Krug, T., Srivastava, N., Jamsranjav, B., Fukuda, M., & Troxler, T. (2013). *2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol.* Switzerland.

Hoelscher, M.T., Nehls, T., Jänicke, B., & Wessolek, G. (2016). Quantifying cooling effects of facade greening: Shading, transpiration and insulation. *Energy Build.*, Vol.114, 283–290. doi:10.1016/j.enbuild.2015.06.047

Holm, D. (1989). Thermal improvement by means of leaf cover on external walls—A simulation model. *Energy and Buildings*, Vol.14: 19-30.

Hoyano, A. (1988). Climatological uses of plants for solar control and the effects on the thermal environment of a building. *Energy and Buildings,* Vol.11: 181-199.

Huang, Z., Lu, Y., Wong, N. H., & Poh, C. H. (2019), The true cost of “greening” a building: Life cycle cost analysis of vertical greenery systems (VGS) in tropical climate, *Journal of Cleaner Production*, Vol. 228, pp 437-454, 0959-6526, doi:10.1016/j.jclepro.2019.04.275.

Hunter, A.M., Williams, N.S.G., Rayner, J.P., Aye, L., Hes, D., & Livesley, S.J. (2014). Quantifying the thermal performance of green facades: A critical review. *Ecol. Eng.,* Vol. 63, 102–113. doi:10.1016/j.ecoleng.2013.12.021

Hunukumbura, W.M.D. (1999). *Eco friendly architecture: an examination of tropical examples with special reference to tourist architecture in Sri Lanka* [Unpublished dissertation]. University of Moratuwa.

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.

Hyde, R.A., Rajapaksha, I., Groenhout, N., Barram, F., Shahriar, A.N.M., Candido, C., & Rajapaksha, U. (2009). Towards a methodology for retrofitting commercial buildings using bioclimatic principles, *in proceedings of 43rd Annual Conference of the Architectural Science Association, ANZAScA 2009*, University of Tasmania

Hyde, R. (2000). *Climate responsive design.* London: E&FN Spon.

Ibrahim, N.L.N., Hayman, S., & Hyde. R. (2010). A Typological Approach to Daylighting Analysis.

Ibraheem, Y., Piroozfar, P., & Farr, E.R. (2017). Integrated Façade System for office buildings in hot and arid climates: A comparative analysis. In *Building Information Modelling, Building Performance, Design and Smart Construction*, pp. 273-288.

Ingrao, C., Messineo, A., Beltramo, R., Yigitcanlar, T., & Ioppolo, G. (2018). How can life cycle thinking support sustainability of buildings? Investigating life cycle assessment applications for energy efficiency and environmental performance. *J. Clean. Prod.,* Vol. 201, 556e569.

Intergovernmental Panel on Climate Change. (2007). *Climate Change 2007: Impacts, Adaptation, and Vulnerability*, in IPCC Fourth Assessment Report, Cambridge University Press.

Isobe, M. (2013). Impact of global warming on coastal structures in shallow water. *Ocean Engineering*, Vol. 71, pp. 51–57.

Jänicke, B., Meier, F., Hoelscher, M. & Scherer, D. (2015). Evaluating the Effects of FaçadeGreening on Human Bioclimate in a Complex Urban Environment. *Advances in Meteorology*, pp. 1-15.

Jayakody, G. D. C. (2020). *Evaluation of economic value of vertical greenerues of Sri Lanka; A simulation by design builder* [Unpublished dissertation], University of Ruhuna.

Jefas, M., & Silva, N. D. (2013). Implement the vertical greenery wall (facade) to multi-stored building in Sri Lankan Context

Jim, C.Y. (2015). Green wall classification and critical design-management assessments. *Ecol. Eng.,* Vol. 77, pp. 348–362.

Jim, C.Y., & Chen, W.Y. (2006). Perception and attitude of residents toward urban green spaces in Guangzhou (China). *Environ. Manage*. Vol. 38, 338–349. doi:10.1007/s00267-005-0166-6

Jim, C.Y., & Chen, S.S. (2003). Comprehensive greenspace planning based on landscape ecology principles in compact Nanjing city, China. Landsc. *Urban Plan.,* Vol. 65, pp. 95–116. doi:10.1016/S0169-2046(02)00244-X

Johnston, F. M., & Johnston, S. W. (2004) Impacts of road disturbance on soil properties and on exotic plant occurrence in subalpine areas of the Australian alps, Arctic, Antarctic, and Alpine research, Vol. 36:2, pp. 201-207, DOI: 10.1657/1523-0430(2004)036[0201:IORDOS]2.0.CO;2

Johnston, J., & Newton, J. (1996). Building green. A guide for using plants on roofs, wall and pavements. London: The London Ecology Unit; 1996.

Kaloustian, N., & Diab, Y. (2015). Effects of urbanization on the urban heat island in Beirut. *Urban Clim*. Vol. 14, 154–165. doi:10.1016/j.uclim.2015.06.004

Kalnay, E., & Cai, M. (2003). Impact of urbanization and land-use change on climate. *Nature,* Vol. 423, 528–531. doi:10.1038/nature01649.1.

Keeler, M., & Burke, B. (2009). Fundamentals of Integrated Design for Sustainable Building. Hoboken, NJ: John Wiley and Sons, Inc.

Kenneth, I. p., Lam, M., & Miller, A. (2010). Shading performance of a vertical deciduous climbing plant canopy, Building and Environment, Vol. 45, pp. 81–88.

Khan, M.A., Amin, N., Khan, A., Imtiaz, M., Khan, F., Ahmad, I., Ali, A., & Islam, B. (2016). Plant therapy: a nonpharmacological and noninvasive treatment approach medically beneficial to the wellbeing of hospital patients. *Gesunde Pflanz*. Vol. 68 (4), 191e200.

Köhler, M. (2008). Green facades-a view back and some visions. *Urban Ecosyst*. Vol. 11, 423–436.doi:10.1007/s11252-008-0063-x

Kong, F., & Nakagoshi, N. (2006). Spatial-temporal gradient analysis of urban green spaces in Jinan, China. *Landsc. Urban Plan*., Vol. 78, 147–164. doi: 10.1016/j.landurbplan.2005.07.006

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, *Economic Botany*, Vol. 67(4), pp. 335–349. doi: 10.1007/s12231-013-9251-6.

Krusche, P., Krusche, M., Althaus, D., & Gabriel, I. (1982). O¨ kologisches bauen, Herausgegeben vom umweltbundesamt, Bauverlag.

Langer, I., Sodoudi, S., & Cubasch, U. (2012). Using the ENVI-MET program to simulate the micro climate in new Town Hashtgerdh. *The international conference on Computing, Networking and Digital Technolog*

Lee, B. J., Jang, T. Y., Wang, W., & Namgung, M. (2009). Design criteria for an urban sidewalk landscape considering emotional per- ception. *J. Urban Plann. Dev*., Vol. 135(4), pp. 133–140.

Lean, H. H., & Smyth, R. (2009). *CO_2 Emissions, Electricity Consumption and Output In Asia.* (Development Research Unit Working Paper Series No. 13-09). Monash University, Department of Economics.

Li, J., Wai, O.W.H., Li, Y.S., Zhan, J., Ho, Y.A., Li, J., & Lam, E. (2010). Effect of green roof on ambient CO_2 concentration. Vol. 45, pp. 2644–2651. doi:10.1016/j.buildenv.2010.05.025

Li, L., & Pussella, P.G.R.N. (2017). Is colombo city, Sri Lanka secured for urban green space standards? *Appl. Ecol. Environ. Res.*, Vol. 15, pp. 1789–1799. doi:10.15666/aeer/1503

Li, Y., Zhu, L., Zhao, X., Li, S., & Yan, Y. (2013). Urbanization impact on temperature change in china with emphasis on land cover change and human activity. *J. Clim*. Vol. 26, pp. 8765–8780. doi:10.1175/JCLI-D-12-00698.1

Lisa, G. (2009) Sensitivity of Building Zones to Potential Global Warming. *Architectural Science Review* Vol. 52:4, pp. 279-294.

Loh, S. (2008). *Living walls – A way to green the built environment. Environment design guide*. Australian Institute of Architects.

Lunain, D., Ecotiere, D., & Gauvreau, B. (2016). In-situ evaluation of the acoustic efficiency of a green wall in urban area. pp. 6592–6601

Maas, J., Verheij, R.A., Groenewegen, P. P., Vries, S. De., & Spreeuwenberg, P. (2006). Green space, urbanity, and health: how strong is the relation? *J. Epidemiol. Community Heal*., Vol. 60, pp. 587-592.doi:10.1136/jech.2005.043125

Macilwain, C. (2000). Global-warming sceptics left out in the cold. *Nature*, Vol. 403(6767), pp. 233–233. Retrieved from http://www.nature.com/nature/journal/v403/n6767/full/403233a0.html doi: 10.1038/35002154

Mage, D., Webster, A., Peterson, P., Ozolins, G., Orthofer, R., Vandeweerd, V., & Gwynne, M. (1996). Urban air pollution in megacities of the world. *Atmos. Environ.*, Vol. 30, pp. 681–686.

Mahdiyar, A., Tabatabaee, S., Nobahar Sadeghifam, A., Reza Mohandes, S., Abdullah, A., & Moharrami M. M. (2016). Probabilistic private cost-benefit analysis for green roof installation: A Monte Carlo simulation approach. *Urban For. Urban Gree.*, Vol. 20, 317327.

Majeed, M. (1998). Analysis of Urbanization Trends in the Greater Colombo Area from 1956 to 1994 Using Air Photos. *Built-environment - Sri Lanka*, Vol.1, pp. 19–22.

Manso, M., & Castro-Gomes, J. (2014). Green wall systems: A review of their characteristics. *Renew. Sustain. Energy Rev*., Vol. 41, 863–871. doi:10.1016/j.rser.2014.07.203

Marchi, M., Pulselli, R.M., Marchettini, N., Pulselli, F.M., & Bastianoni, S. (2014). Carbon dioxide sequestration model of a vertical greenery system. *Ecol. Modell.* https://doi.org/10.1016/j.ecolmodel.2014.08.013

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

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, *Building and Environment*, Vol. 64, pp. 57–66. doi: 10.1016/j.buildenv.2013.03.005.

Mazzali, U., Peron, F., & Scarpa, M. (2012). Thermo-physical performances of living walls via field measurements and numerical analysis. *In: Eco-architecture IV. Harmonisation between architecture and natureWIT transactions on ecology and the environmen*t, Vol. 165; 2012, ISBN 978-1-84564-614-1; 2012. p. 239e50.http://dx.doi.org/10.2495/ARC120011; 2012.

McPherson EG, Nowak DJ, & Rowntree R. A. (1994). *Chicago's urban forest ecosystem: results of the Chicago urban forest climate project.* Gen Tech Rep NE-186. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Radnor Corporate Center, Pennsylvania.

Mc Pherson, E.G., Scott, K.I., & Simpson, J. R. (1998). Estimating cost effectiveness of residential yard trees for improving air quality in Sacramento, California, using existing models. *Atmospheric Environment*, Vol. 32(1):75e84

Meier, K. (2010). Strategic landscaping and air-conditioning savings: a literature review. *Energy Build.*, 1516, 479486

MEWR, M. (2014). *Our Home Our Environment Our Future, Sustainable Singapore Blueprint 2015*, Ministry of the Environment and Water Resources. MEWR) & Ministry of National Development (MND).

Ministry of Manpower, (2016). *Medical insurance requirements for foreign worker*. http://www.mom.gov.sg/passes-and-permits/workpermit-for-foreign worker/sector-specific-rules/medical-insurance.

Nisansala, S., & Halwathura, R.U. (2011). Amplification of comfort and the air quality with green roof in cities.

Nordell, B. (2003). Thermal pollution causes global warming. *Global and Planetary Change*, Vol. *38*(34), 305–312. Retrieved from http:// www.sciencedirect.com/science/article/pii/S0921818103001139 doi: 10.1016/S0921-8181(03)00113-9

NParks, (2017). *Landscape excellence assessment framework (LEAF),* National parks board. from. https://www.nparks.gov.sg/partnerus/landscapeindustry/leaf

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

Oke, T.R. (1982). The energetic basis of the urban heat island. *Q. J. R. Meteorol. Soc*. Vol. 108, pp. 1–24. doi:10.1002/qj.49710845502

Oke, T.R. (1978). *Boundary Layer Climates, Methuen, London*. Second Edition. Taylor and Francis. pp. 227-357

Ottele, M., Perini, K., Fraaj, A.L.A., Haas, E. M., & Raiteri, R. (2011). Comparative life cycle analysis for green façades and living wall systems. *Energy Build*., Vol. 43 (12), 3419e3429.

Ottelé, M., van Bohemen, H. & Fraaij, A. (2010). Quantifying the deposition of particulate matter on climber vegetation on living walls. *Ecological Engineering*, Vol. 36(2), 154-162.

Pachauri, R. K., & Mayer, L. (2015). Intergovernmental Panel on Climate Change (Eds.). (2015). *Climate change 2014: synthesis report*. Geneva, Switzerland: Intergovernmental Panel on Climate Change

Parker, J.H. (1987). The use of shrubs in energy conservation in plantings. *Landscape J.*, Vol 6, pp. 132–139.

Peck, S.W., Callaghan, C., Kuhn, M.E., & Bass, B. (1999). *Greenbacks from green roofs: forging a new industry in Canada*, status report on benefits, barriers and opportunities for green roof and vertical garden technology diffusion

Peiris, M., Sooriyanayaka, J., Samarasinghe, S., Lakmal, A., & Chandrathilake, S. (2014). Analysis of thermal effectiveness in Sri Lankan context a research based on vertical greeneries of multi-storied buildings, *in proceedings of KDU International Research Conference -2014*. pp. 109–116.

Pérez, G., Coma, J., Martorell, I. & Cabeza, L.F. (2014), Vertical Greenery Systems (VGS) for energy saving in buildings: a review, *Renewable and Sustainable Energy Reviews*, Vol. 39, pp. 139-165.

Pérez, G., Rincón, L., Vila, A., González, J.M., & Cabeza, L.F. (2011b). Green vertical systems for buildings as passive systems for energy savings. *Appl. Energy*, Vol. 88, pp. 4854–4859.

Perez, G., Rincon, L., Vila, A., Gonzales, J.M., & Cabeza, L.F. (2011a). Behavior of green facades in Mediterranean Continental climate. Port. SB10 *Sustain. Build. Afford. To All*, Vol. 52, pp. 1861–1867. https://doi.org/10.1016/j.enconman.2010.11.008

Perini, K., & Ottelé, M. (2014). Designing green façades and living wall systems for sustainable constructions. *Int. J. Des. Nat. Ecodyn*. Vol. 9 (1).

Perini, K., Ottelé, M., Fraaij, A.L.A., Haas, E.M., & Raiteri, R. (2013). Vertical greening systems and the effect on air flow and temperature on the building envelope. *Build. Environ.*, Vol. 46, pp. 2287–2294.

Perini, K., & Rosasco, P. (2013). Cost–benefit analysis for green façades and living wall systems. *Build. Environ.,* Vol. 70, pp. 110–121. https://doi.org/10.1016/j.buildenv.2013.08.012.

Perini, K. (2012). *The Integration of Vegetation in Architecture: Innovative Methods and Tools* [Unpublished dissertation]. University of Genoa.

Perini, K., Ottelé, M., Haas, E. & Raiteri, R. (2011a). Greening the building envelope, façade greening and living wall systems. *Open Journal of Ecology*, Vol. 1(1), pp. 1-8.

Perini, K., Ottelé, M., Fraaij, A., Haas, E. & Raiteri, R. (2011b). Vertical greening systems and the effect on air flow and temperature on the building envelope. *Building and Environment*, Vol. 46(11), pp. 2287-2294.

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

Population Reference Bureau. (2015). *World population data sheet*. doi:10.2307/1972177

Population Reference Bureau. (2007). *World Population Highlights: Key Findings from PRB's 2007 World Population Data Sheet*. Popul. Bull. Vol. 62, pp. 3–16.

Poumanyvong, P., Kaneko, S., & Dhakal, S. (2012). Impacts of urbanization on national transport and road energy use: Evidence from low, middle and high income countries. *Energy Policy,* Vol. 46, 268–277. doi:10.1016/j.enpol.2012.03.059

Pe´rez, 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. Energy* Vol. 187, 424437.

Pe´rez, G., Rincon, L., Vila, A., Gonzalez, J.M., & Cabeza, L.F. (2011). Green vertical systems for buildings as passive systems for energy savings. *Appl. Energy,* Vol. 12, 4854 e 4859.

Prez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. *Energy and Buildings*, Vol. 40(3), 394–398. Retrieved from http://www.sciencedirect.com/science/article/ pii/S0378778807001016 doi: 10.1016/j.enbuild.2007.03.007

Pe´rez-Urrestarazu, L., Ferna´ndez-Can˜ero, R., Franco-Salas, A., & Egea, G. (2015). Vertical greening systems and sustainable cities. *J. Urban Technol*., Vol. 22 (4), 6585. Available from: https://doi. org/10.1080/10630732.2015.1073900.

Perez-Urrestarazu, L., Egea, G., Franco-Salas, A., & Fernandez-Canero, R. (2014). Irrigation systems evaluation for living walls. *J. Irrigat. Drainage Eng*., Available from: https://doi.org/ 10.1061/(ASCE)IR.1943-4774.0000702.

Price, D. (1995). Energy and human evolution. *Population and Environment: A Journal of Interdisciplinary Studies*, 301-319.

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*, Vol. 82 (8), pp. 727–745.

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

Rajapaksha, U., Rupasinghe, H.T., & Rajapaksha, I., (2015). Resolved duality: external double skin envelopes for energy sustainability of office buildings in the tropics. *In:Proceedings of 31st International Conference of Passive and Low Energy Architecture Conference* held in September 9-11. Bologna, Italy.

Rajapaksha, U. (2013). Design solution sets for sustainable retrofit. In R. Hyde (Eds.), *Sustainable retrofitting of commercial high-rise buildings in warm climates.* London: Earthscan E and Spon

Rajapaksha, I. (2014). Mythology of architecture. *Sri Lanka Architect*.

Raji, B., Tenpierik, M. J. & van den Dobbelsteen, A. (2015). The impact of greening systems on building energy performance: A literature review. *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, Vol. 45, pp. 610–623. doi: 10.1016/j.rser.2015.02.011.

Rayner, J.P., Raynor, K.J., & Williams, N.S.G. (2010). Facade greening: A case study from Melbourne, Australia, in: *International Conference on Landscape and Urban Horticulture. Richmond*, 3121, Victoria Australia, pp. 709–713.

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

Rupasinghe, H.T., Perera, T.A.N.T., & Halwatura, R.U. (2018). Towards greener cities; Investigating the potentials of vertical greening in tropics as a design approach to create sustainable urban environments. In: *Proceedings of the 6th International Conference on 'Cities, People and Places'- ICCPP-2018* October 05th –06th. 2018, Colombo, Sri Lanka.

Rupasinghe, H.T. (2016), Assessing external double skin envelopes coupled with night ventilation and thermal mass for passive cooling in the tropics, in Proceedings of *50th International conference of the Architectural Science Association 2016.*

Rupasinghe, H.T. (2015), *External double skin envelops for energy efficiency: towards a true green approach in non-domestic buildings in the tropics* [Unpublished dissertation], University of Moratuwa.

Safikhani, T., Abdullah, A.M., Ossen, D.R., & Baharvand, M. (2014). A review of energy characteristic of vertical greenery systems. *Renew. Sustain. Energy Rev*., Vol.40, pp. 450–462. doi:10.1016/j.rser.2014.07.166

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

Samaranayake, S.U., & Silva, D. (2010). Effect of green workplace environment on employee performance, in: *International Conference on Sustainable Built Environment (ICSBE-2010),* Kandy, pp. 417–425.

Schau, E. M., Traverso, M., Lehmann, A., & Finkbeiner, M. (2011). Life cycle costing in sustainability assessment—A case etudy of remanufactured alternators. *Sustainability*, Vol. *3*(11), 2268–2288. https://doi.org/10.3390/su3112268

Scott, M.J., Wrench, L.E., & Hadley, D.L. (1994). Effects of climate change on commercial building energy demand. *Energy Sources,* Vol. 16, pp. 317–332. doi:10.1080/00908319408909081

Sheweka, S.M., & Mohamed, N.M. (2012). Green facades as a new sustainable approach towards climate change. *Energy Procedia,* Vol 18, pp. 507–520. doi:10.1016/j.egypro.2012.05.062

Shiah, K., & Kim, J. (2011). *An investigation into the application of vertical garden at the new SUB atrium,* University of British Columbia. Student report. Columbia. doi:10.14288/1.0108430

Snodgrass, E. C., & Snodgrass, L. L. (2006). *Green roof plants: a resource and planting guide* (No. 04; SB419. 5, S5.). Portland, OR: Timber Press.

Son, J. S., Sumayo, M., Hwang, Y. J., Kim, B. S., & Ghim, S. Y. (2014). Screening of plant growth-promoting rhizobacteria as elicitor of systemic resistance against gray leaf spot disease in pepper. *Applied soil ecology,* Vol. *73,* pp. 1-8.

Stazi, F, Tomassoni, F, & Vegliò, A. (2011). Experimental evaluation of ventilated walls with an external clay cladding. *Renewable Energy*, Vol. 36, pp. 3373–3385.

Stec, W.J., & Van Paassen, A.H.C. (2005). Symbiosis of the double skin façade with the HVAC system. *Energy and Buildings,* Vol.37, pp. 461–469.

Stigsdotter, U.A., & Grahn, P. (2004). A garden at your workplace may reduce stress. *Des. Health,* 147e157.

Subasinghe, S., Estoque, R., & Murayama, Y. (2016). Spatiotemporal analysis of urban growth using GIS and remote sensing: a case study of the colombo metropolitan area, Sri Lanka. ISPRS *Int. J. Geo-Information* Vol. 5, 197. doi:10.3390/ijgi5110197

Sunakorn, P., & Yimprayoon, C. (2011). Thermal performance of bio facade with natural ventilation in the tropical climate. *Procedia Eng.,* Vol. 21, pp. 34–41. doi: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, *Building and Environment,* Vol. 67, pp. 1-13.

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*., Vol.32 (1), 443–454.

Tilley, D., Alexander, A., Chang, A., Price, C., Welch, A., Brian, T., and 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.

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. Vol. 62 (1), pp. 35–46. https://doi.org/10.1080/00038628.2018.1534724.

Tam, B.Y., Gough, W.A., & Mohsin, T. (2015). The impact of urbanization and the urban heat island effect on day to day temperature variation. *Urban Clim*., Vol. 12, pp. 1–10. doi:10.1016/j.uclim.2014.12.004

Tan, C.L., Wong, N. H., & Jusuf, S. K. (2014). Effects of vertical greenery on mean radiant temperature in the tropical urban environment. *Landscape and Urban Planning*. Vol. 127, 0169-2046

Tan, J., Zheng, Y., Tang, X., Guo, C., Li, L., Song, G., Zhen, X., Yuan, D., Kalkstein, A.J., Li, F., & Chen, H. (2010). The urban heat island and its impact on heat waves and human health in Shanghai. *Int. J. Biometeorol*., Vol. 54, pp. 75–84. doi:10.1007/s00484-009-0256-x

Tan, P. Y., & Sia, A. (2009) Understanding the performance of plants on non-irrigated green roofs in Singapore using a biomass yield approach, *Nature in Singapore,* pp 149-153, National University of Singapore

Tombazis, A.N. (1996) On skins and other preoccupations of architectural design, *Renewable Energy*, Vol. 8, Issues 1–4, pp. 51-55, ISSN 0960-1481, https://doi.org/10.1016/0960-1481(96)88819-7.

Tran, H., Uchihama, D., Ochi, S., & Yasuoka, Y. (2006). Assessment with satellite data of the urban heat island effects in Asian mega cities. *Int. J. Appl. Earth Obs. Geoinf.,* Vol. 8, pp. 34–48. doi:10.1016/j.jag.2005.05.00

United Nations. (2019). Population Division: *World Urbanization Prospects: The 2019 revision,* Department of Economic and Social Affairs, Population Division, United Nations, New York.

United Nations. (2014). *World Urbanization Prospects: The 2014 Revision*, Department of Economic and Social Affairs, Population Division, United Nations, New York.

United Nations. (2011). *World urbanization prospects: the 2011 revision*. United Nations Department of Economic and Social Affairs, Population Division, New York, New York, USA. [online] URL: http://esa.un.org/unup/.

Urban Redevelopment Authority. (2014). *Circular Package: Landscaping for Urban Spaces and High-rises* (LUSH) 2.0 programme.

USEPA. *Green Building Strategy*. (2008). Retrieved, from USEPA (United States Environmental Protection Agency): Environmental Protection Agency) (2008). EPA Green Building Strategy. Retrhttp://www.epa.gov/greenbuilding/ pubs/ greenbuilding_strategy_

Veisten, K., Smyrnova, Y., Klæboe, R., Hornikx, M., Mosslemi, & M., Kang, J. (2012). Valuation of green walls and green roofs as soundscape measures: including monetised amenity values together with noise-attenuation values in a cost-benefit analysis of a green wall affecting courtyards. *Int. J. Environ. Res. Public Health,* Vol. 9, 37703788

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 Forestry & Urban Greening*. Vol. 27, pp. 173–186.doi: 10.1016/j.ufug.2017.07.005.

Weng, Q., Lu, D., & Schubring, J. (2004). Estimation of land surface temperature-vegetation abundance relationship for urban heat island studies. *Remote Sens. Environ*., Vol. 89, pp. 467–483. doi:10.1016/j.rse.2003.11.005

White, E. V., & Gatersleben, B. (2011). Greenery on residential buildings: Does it affect preferences and perceptions of beauty? *J. Environ. Psychol.,* Vol. 31, pp. 89–98. doi:10.1016/j.jenvp.2010.11.002

White, J.W. & Snodgrass, E. (2003). Extensive greenroof plant selection and characteristics *Proc. 1st Intl. Green Roof Conf.: Greening rooftops for sustainable communities,* 1 166 176

World Health Organization. (2000). *Air Quality Guidelines for Europe, in: WHO Regional Publications*, European Series, No. 91., pp. 149–186.

Wickramasinghe, L.S., Subasinghe, S.M.C.U.P., & Ranawala, S.M. (2016). Spatial and temporal changes of the green cover of colombo city in sri lanka from 1956 to 2010. *J. Environ. Prof. Sri Lanka,* Vol. 5, pp. 53–66.

Wijayatunga, P.D.C., Fernando, W.J.L.S, & Shrestha, R.M. (2003) Greenhouse gas emission mitigation in the Sri Lanka, power sector supply side and demand side options, *Energy Conservation and Management,* Vol. 44, pp. 3247-3265.

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

Wong, N.H., Tan, A.Y.K., Tan, P.Y., Sia, A., & Wong, N.C. (2010b). Perception Studies of Vertical Greenery Systems in Singapore. *J. Urban Plan. Dev*. Vol. 136, pp. 330–338. doi:10.1061/(ASCE)UP.1943-5444.0000034

Wong, PC, Prasad, D., &Behnia, M. (2008). A new type of double-skin façade configuration for the hot and humid climate. *Energy and Buildings,* Vol.40, pp. 1941–1945.

Yuen, B., & Hien, W.N. (2005). Resident perceptions and expectations of rooftop gardens in Singapore. *Landsc. Urban Plan.* Vol. 73, pp. 263–276. doi:10.1016/j.landurbplan.2004.08.001

Zhang, T., Zheng, J., Yu, Z., Gu X., Tian, X., Peng, C., & Chow, W. S. (2018) Variations in photoprotective potential along gradients of leaf development and plant succession in subtropical forests under contrasting irradiances. *Environmental and Experimental Botany*, Vol. 154, pp. 23-32, 0098-8472, doi:10.1016/j.envexpbot.2017.07.016

Appendix A: Sample questionnaires

Sample questionnaire – Perception of general public on vertical greening

Dear sir/madam,

Good day! We are conducting a survey (Research study) to evaluate the human perception and performance of vertical greening in Colombo context. Your answers will be helpful to enhance our final research findings and only these answers will be considered to evaluate the human perception for green facades. We kindly request your valuable time to provide answers and suggestions. Thank you.

Date: …………………. Time: …………………….

Location: …………………………

Personal details

- Age group (years): 18-25 - ☐ 25-35 - ☐ 35-45 - ☐ 45-55 - ☐ above 55 - ☐
- Gender: Male ☐ Female ☐
- Are you aware of vertical greening typologies and systems? Yes / No
- Have you seen / notice the green façade/ green wall in the building? Yes / No
  If yes, is it,
  - At first sight ☐
  - Not at first ☐
  - Someone else showed ☐
- According to your opinion, what would be the purpose of having the façade in the building? (give all applicable answers)
  - Aesthetics and appearance ☐
  - Heat gain reduction ☐
  - Promotion of ventilation ☐
  - Noise attenuation ☐
  - Other ☐

If other please state the purpose: ……..……………………………………………

- Do you think vertical greening is beneficial and environmentally friendly?

  Yes ☐

  No ☐

  Maybe ☐

- Indicate your level of agreement or disagreement on the following statements

	Strongly agree	Agree	Disagree	Strongly disagree	No idea
Vertical greening adds extra beauty to the building	☐	☐	☐	☐	☐
Vertical greening traps dust from outside	☐	☐	☐	☐	☐
Vertical greening blocks noise from outside	☐	☐	☐	☐	☐
Vertical greening reduce heat in the surrounding	☐	☐	☐	☐	☐
Vertical greening gives visual satisfaction	☐	☐	☐	☐	☐

- Indicate your level of satisfaction on the following statements

	Highly satisfied	Satisfied	Unsatisfied	Highly unsatisfied	No idea
Feeling near the vertical greening	☐	☐	☐	☐	☐
Effect of on your mental condition	☐	☐	☐	☐	☐

- Have you seen a building before vertical greening integration? Yes / No

- If yes, what would you prefer,
  - Building before vertical greening ☐
  - Building after vertical greening ☐
  - No change in preference ☐
- Give reasons to your answer for above question (write your own idea)

  ………………………………………………………………………………………

- Do you have green façade at your home? Yes / No

  If yes, what is the reason of having a green façade at your place?

  ………………………………………………………………………………………

- Would you like to have a green façade at your own? Yes / No

  Briefly give the reason for your answer

  ……………………………………………………………………………..

- As you think, what could be troublesome issue of having a green façade at home?
  ………………………………………………………………………………………

- Do you think vertical greening is sustainable?

  Yes ☐

  No ☐

  Maybe ☐

  Briefly give the reason for your answer

  ……………………………………………………………………………..

Thank you for kind co-operation. Enjoy the day!

Sample questionnaire – Occupant satisfaction survey on vertical greening

Dear sir/madam,

Good day! We are conducting a survey (Research study) to evaluate the human perception and performance of existing green façade (green walls) in Colombo context. Your answers will be helpful to enhance our final research findings and only these answers will be considered to evaluate the human perception for green facades. We kindly request your valuable time to provide answers and suggestions. Thank you.

Date: …………………. Time: ……………………. ……….

Location: ……………… Building name: ……………………

Type of building: Hotel / Office/ Residential

Personal details

- Age group (years): 18-25 - ☐ 25-35 - ☐ 35-45 - ☐ 45-55 - ☐ above 55 - ☐
- Gender: Male ☐ Female ☐
- Role in the building:

  Hotel / Office: Occupant ☐ Customer ☐

  How long have you been working here? ....

  Residence: - Family member ☐ Neighbor ☐

  How long have you been living here? …………………….

- Have you seen / notice the green façade/ green wall in the building? Yes / No

  If yes, is it,

  At first sight ☐

  Not at first time ☐

  Accidently ☐

  No special attention given ☐

  Someone else showed ☐

- According to your opinion, what would be the purpose of having vertical greening in the building?
  ………………………………………………………………

- Is the vertical greening system visible to you, when you are at work? Yes / No

- Does it cover you from direct sun light at any time of the day? Yes / No

- Indicate your level of satisfaction on the following statements

	Highly satisfied	Satisfied	Unsatisfied	Highly unsatisfied	No idea
How do you feel near vertical greening	☐	☐	☐	☐	☐
Effect of vertical greening on your mental condition	☐	☐	☐	☐	☐
How satisfied are you on working in a building with vertical greening	☐	☐	☐	☐	☐

- Have you ever been near the green façade? (In front / Behind / Both)

- How satisfied are you about heat reduction and light penetration through vertical greening?

	Highly satisfied	Satisfied	Unsatisfied	Highly unsatisfied	No idea
Level of heat reduction from the vertical greening	☐	☐	☐	☐	☐
Level of light penetration through vertical greening	☐	☐	☐	☐	☐

- How do you feel near the green façade?

☐ It is bit hotter than outside
☐ It is bit cooler than outside
☐ It is same as outside
☐ No idea

☐ It is visually comfortable
☐ It disturbs to eye sight
☐ It doesn't influence comfort
☐ No idea

- Please indicate your level of agreement or disagreement for the following statements.

	Strongly agree	Agree	Disagree	Strongly disagree	No idea
Vertical greening adds extra beauty to the building	☐	☐	☐	☐	☐
Vertical greening traps dust from outside	☐	☐	☐	☐	☐
Vertical greening blocks noise from outside	☐	☐	☐	☐	☐
Vertical greening reduce heat in the surrounding	☐	☐	☐	☐	☐
Vertical greening gives visual satisfaction	☐	☐	☐	☐	☐

- What is your preference of having a green façade in the building?

Least	0	1	2	3	4	5	6	7	Most

- Have you been here (working/ visiting/living) before the construction of the green façade in this building? Yes / No

- If yes, what do you prefer,

  The building condition before green façade ☐

  The building condition after green façade ☐

  No change in preference ☐

- Give reasons to your answer for above question (write your own idea)

  ………………………………………………………………………………

- If you are an occupant, do you have green façade at your home? Yes / No

  If yes, what is the reason of having a green façade at your place?

  ………………………………………………………………………………

- Would you like to have a green façade at your own? Yes / No

  If yes, what would be the reason of having a green façade at your place?

  ………………………………………………………………………………

- As you think, what could be troublesome issue of having a green façade?

  ………………………………………………………………………………

Thank you for kind co-operation. Enjoy the day!

Sample questionnaire – Designer perception on vertical greening

Dear sir/madam,

Good day! Please kindly co-operate to the research survey on designer perception on trend of vertical greening and on existing vertical greening in Sri Lankan context by giving your true answers for the below questions.

Date: …………………. Time: …………………….

Personal details

- Age group (years): 18-25 - ☐ 25-35 - ☐ 35-45 - ☐ 45-55 - ☐ above 55 - ☐
- Gender: Male ☐ Female ☐
- How long have you been practicing architecture in Sri Lanka?

  01-05 - ☐ 05-10 - ☐ 10-15 - ☐ 15-20 - ☐ above 20 - ☐

- Do you consider sustainable design strategies when developing design concepts?

  Yes ☐

  No ☐

  Sometimes ☐

  Briefly explain your answer

  ………………………………………………………………………………

  ………………………………………………………………………………

- Are you aware of vertical greening typologies and systems? Yes / No

- What do you think of the concept of vertical greening and new vertical greening trends?

  Highly acceptable ☐

  Acceptable ☐

  Unacceptable ☐

  Highly unacceptable ☐

  Nothing specific ☐

  Other ☐

- Have you integrated vertical greening concept in your designs? Yes / No

  If yes, what were the main purposes of integrating green facades in building?

  ………………………………………………………………………………..

  What were the feedback from the clients of such buildings?

  Highly satisfied ☐

  Satisfied ☐

  Unsatisfied ☐

  Highly unsatisfied ☐

  Nothing specific ☐

- Have any client specifically requested for vertical greening integration?

  Yes / No

- According to your opinion, what are the other reasons of integrating green facades in building?

  ………………………………………………………………………………

- Do you think vertical greening is beneficial and environmentally friendly?

  Yes / No

  Briefly state the reason

  ………………………………………………………………………………………

- Please indicate your level of agreement or disagreement for the following statements.

	Strongly agree	Agree	Disagree	Strongly disagree	No idea
Vertical greening enhances the aesthetic appeal	☐	☐	☐	☐	☐
Vertical greening traps dust from outside.	☐	☐	☐	☐	☐
Vertical greening blocks noise from outside	☐	☐	☐	☐	☐
Vertical greening reduces the indoor overheating	☐	☐	☐	☐	☐
Vertical greening reduces the outdoor air temperature	☐	☐	☐	☐	☐
Vertical greening gives visual satisfaction	☐	☐	☐	☐	☐

- According to your opinion what are the other benefits of integrating vertical greening

………………………………………………………………………………………

- How do you feel near the green façade?

  Highly satisfied ☐

  Satisfied ☐

  Unsatisfied ☐

  Highly unsatisfied ☐

  Nothing specific ☐

- The effect of vertical greenery on enhancing building users' mental condition

  Highly effective ☐

  Effective ☐

  Ineffective ☐

  Highly ineffective ☐

  Nothing specific ☐

- What benefits would the outsiders have from a vertical greened building?

  ……………………………………………………………………………………

- What benefits would the building occupants have from a vertical greened building?

  ……………………………………………………………………………………

- Have you seen any of the vertical greened building before the construction of the green façade?

  Yes / No

- If yes, what do you prefer,

  The building condition before green façade ☐

  The building condition after green façade ☐

  No change in preference ☐

- Give reasons to your answer for above question (write your own idea)

  ……………………………………………………………………………………

- Have you taken any building integrated with vertical greenery for precedence?

  Yes / No

  If yes, state some of the buildings

  ……………………………………………………………………………………

- Would you like to recommend vertical greening in your future designs?

    Yes / No

  Briefly state the reason for your answer

  ………………………………………………………………………………………

- What are the main issues related to existing vertical greening according to your perception?

  ………………………………………………………………………………………

- Do you think vertical greening would be a better strategy for sustainable development?

    Yes / No

  State your reasons briefly

  ………………………………………………………………………………………

Thank you for kind co-operation. Enjoy the day!

Appendix B: Sample building data collection sheet

Data collection No. 01 - Building characteristics

Date: Contact number:

Building name:

Building type: 1. Hotel / Residential / Office /…………………………. 2. Single / multi storey - …………

Location:

Level of urbanization:

Green Façade type: Direct / Indirect / Living wall ……………………………...

Façade orientation: …………………………………………………………………..

Plant type in use: …………………………………………………………………..

Plant condition: ………………………………… … (Well grown/green/brown)

Plant / façade age: …………………………………………………………………...

Façade thickness (approx.): …………………………………………………………………...

Wall material: …………………………………………………………………..

Façade supporting material (if any): …………………………………………………………………..

Façade air cavity thickness: …………………………………………………………………..

Any Comment:

………..

………..

………..

………..

Appendix C: Temperature readings of field investigations

Living Walls

Outer wall						
	Case 01		Case 02		Case 03	
Time	Shaded Wall surface LW1	Bare Wall surface BW1	Shaded Wall surface LW2	Bare Wall surface BW2	Shaded Wall surface LW3	Bare Wall surface BW3
01:00	27	26.65	26.12	25.24	27.98	27.81
02:00	27.2	26.96	25.94	24.85	27.93	26.76
03:00	27	26.7	25.76	24.75	27.87	26.74
04:00	26.9	26.59	25.59	24.67	27.89	26.75
05:00	26.8	25.75	25.44	24.925	27.87	27.39
06:00	28.1	27.97	25.37	25.64	27.55	27.47
07:00	29	29.48	25.99	28.46	27.1	28.39
08:00	30.2	32.06	27.06	31.93	27.85	30.82
09:00	30.2	34.25	27.60	33.65	28.45	33.21
10:00	30.2	37.43	27.85	35.36	29.4	35.36
11:00	30.4	39.21	28.47	36.83	29.79	36.1
12:00	30.3	40.4	28.90	37	29.54	37.51
13:00	30.5	40.65	29.97	39.54	29.88	38.37
14:00	30.1	39.25	29.98	39.96	29.54	38.11
15:00	29.51	38.57	28.77	38.30	29.7	36.56
16:00	29.9	32.33	28.34	37.13	29.5	33.42
17:00	29.2	30.56	27.97	35.36	28.25	30.45
18:00	29.1	30.15	27.67	32.92	28.95	30.415
19:00	29	29.96	27.39	31.65	28.72	29.26
20:00	28.2	28.94	27.17	29.85	28.63	29.24
21:00	28.3	27.74	26.92	28.63	28.29	28.1
22:00	27.7	26.76	26.74	27.83	28.15	28
23:00	27.3	26.25	26.54	27.04	28.09	27.86
24:00	27.2	26	26.32	25.33	28.04	27.82

10 Cm distance						
	Case 01		Case 02		Case 03	
Time	LW1	BW1	LW2	BW2	LW3	BW3
01:00	26.39	27.3	25.3	26.25	27.55	27.72
02:00	26.7	27.5	24.75	25.81	27.5	27.67
03:00	26.44	27.3	24.65	25.6	26.65	27.48
04:00	26.33	27.2	24.5	25.74	26.65	27.49
05:00	26.49	27.1	24.81	25.5	26.29	27.13
06:00	27.71	28.4	26.40	27.3	27.48	27.93
07:00	28.56	29.3	27.54	28.14	28.3	28.9
08:00	29.83	30.42	29.12	29.65	29.46	30.25
09:00	31.5	32.38	30.04	30.68	29.84	30.84
10:00	31.94	32.84	31.45	32.61	31.5	32.53
11:00	32.5	33.59	31.56	32.84	32.15	33.23
12:00	32.2	33.46	31.58	33.21	32.395	33.52
13:00	32	33.72	32.41	34.38	32.54	33.86
14:00	31.8	33.51	32.05	33.94	31.69	32.72
15:00	31.46	33.16	31.52	33.28	31.19	32.24
16:00	30.83	32.47	31.05	32.65	30.75	31.64
17:00	29.57	31.2	30.01	31.12	30.38	30.94
18:00	29.4	30.49	30.40	31.24	30.05	30.55
19:00	29.3	30.06	29.54	30.13	29.16	29.58
20:00	28.5	29.21	29.315	29.65	29.14	29.47
21:00	27.86	28.54	28.75	29.06	28.57	28.89
22:00	26.5	27	28.64	28.88	28.26	28.49
23:00	25.99	26.43	26.69	27.94	27.58	27.79
24:00	25.74	26.25	25.47	26.20	27.56	27.73

1m distance						
	Case 01		Case 02		Case 03	
Time	LW1	BW1	LW2	BW2	LW3	BW3
01:00	27.22	27.12	26.19	26.2	27.66	27.68
02:00	27.41	27.24	25.7	25.76	27.58	27.6
03:00	27.59	27.4	24.6	24.55	27.57	27.59
04:00	27.05	26.98	24.51	24.69	27.57	27.6
05:00	27.15	27.18	24.9	25.05	27.25	27.29
06:00	28.24	28.26	27.18	27.35	27.02	27.22
07:00	29.28	29.33	28.80	28.49	27.84	28.04
08:00	30.32	30.43	30.27	30.07	30.27	30.47
09:00	31.09	31.22	30.81	30.99	30.66	30.86
10:00	31.65	31.9	31.98	32.4	32.15	32.35
11:00	32.09	32.4	32.65	32.51	32.89	33.2
12:00	33	33.14	32.41	32.53	33.1	33.38
13:00	31.96	32.27	32.48	33.16	32.6	33.05
14:00	31.34	31.5	33.20	33.3	32.12	32.41
15:00	31.183	31.29	32.51	32.57	32.21	32.21
16:00	30.32	30.62	31.00	31.07	30.04	30.29
17:00	29.86	29.93	30.78	30.96	30.25	30.5
18:00	29.51	29.69	30.25	30.35	29.87	30.06
19:00	29.21	29.42	30.20	30.28	29.16	29.35
20:00	28.84	28.74	28.98	29.04	29.01	29.2
21:00	28.72	28.71	28.73	28.9	28.81	29
22:00	28.11	27.97	27.55	27.61	28.63	28.65
23:00	27.87	27.69	27.65	27.7	27.93	27.95
24:00	27.58	27.53	27.15	27.15	27.75	27.77

Indirect green facades

Outer wall						
	Case 01		Case 02		Case 03	
Time	Shaded Wall surface IGF1	Bare Wall surface BW1	Shaded Wall surface IGF2	Bare Wall surface BW2	Shaded Wall surface IGF3	Bare Wall surface BW3
01:00	26.39	26.53	26.51	26.64	26.94	27.18
02:00	26.21	26.54	26.14	26.28	27.12	27.38
03:00	26.03	26.42	26.19	26.56	27.18	27.43
04:00	25.84	26.33	26.35	26.74	27.38	27.72
05:00	25.86	26.42	26.76	27.18	27.52	27.97
06:00	25.96	26.87	26.78	27.84	28	29.05
07:00	26.25	29.46	26.55	29.5	28.19	30.48
08:00	27.32	34.93	27.48	35.13	28.34	34.63
09:00	27.86	36.63	28.13	37.43	28.94	34.92
10:00	28.11	37.28	28.44	37.75	29.24	35.28
11:00	28.73	37.74	28.88	38.09	29.7	36.84
12:00	29.16	39	29.06	39	29.84	37.17
13:00	29.24	39.25	29.22	39.18	30.06	37.84
14:00	29.43	39.46	29.48	39.42	29.98	37.48
15:00	29.26	39.21	29.31	38.37	29.64	35.95
16:00	28.61	37.13	29.00	36.49	29.75	34.42
17:00	28.23	35.36	28.65	34.81	29.73	33.35
18:00	27.94	33.92	28.37	33.5	29.43	31.5
19:00	27.65	32.65	28.13	32.32917	28.92	30.8
20:00	27.43	31.58	27.89	31.31	28.4	30.07
21:00	27.18	30.63	27.68	30.45	27.82	29.43
22:00	26.99	29.83	27.51	29.67	27.6	28.72
23:00	26.8	29.04	27.31	28.96	27.42	28.14
24:00	26.58	28.33	27.10	28.36	27.35	28.05

10cm distance						
	Case 01 -NSBM 1		NSBM 2		Case 03 - Sunken	
Time	IGF1	BW1	IGF2	BW2	IGF3	BW3
01:00	25.55	25.62	25.69	25.73	25.62	25.65
02:00	24.99	25.12	25.24	25.29	25.34	25.41
03:00	24.76	24.95	25.08	25.15	25.12	25.26
04:00	24.56	24.65	24.82	24.96	25.35	25.43
05:00	24.66	24.88	24.94	25.12	26.28	26.42
06:00	24.92	25.24	24.19	24.77	26.33	26.68
07:00	25.68	26.15	24.34	24.96	26.46	26.94
08:00	26.21	26.82	25.17	25.84	27.79	28.48
09:00	27.15	27.86	26.64	27.45	28.16	28.88
10:00	28.86	29.65	29.82	30.73	29.49	30.43
11:00	29.67	30.48	30.88	31.92	30.13	31.22
12:00	30.98	32.34	31.18	32.45	30.67	31.84
13:00	31.67	33.32	31.59	33.37	31.35	32.84
14:00	31.77	32.93	31.87	33.24	31.78	33.46
15:00	31.31	32.09	31.32	32.06	31.5	32.53
16:00	30.93	31.64	31.19	31.84	31.23	32.12
17:00	30.21	30.82	30.57	31.15	31.11	31.92
18:00	29.19	29.74	29.47	29.94	30.04	30.68
19:00	28.38	28.91	28.69	29.07	29.17	29.59
20:00	27.73	28.04	27.93	28.27	28.47	28.85
21:00	27.2	27.41	27.26	27.48	27.95	28.16
22:00	26.76	26.82	26.95	27.13	27.82	27.94
23:00	26.27	26.38	26.42	26.54	27.56	27.63
24:00	25.94	26.03	26.09	26.18	26.21	26.26

1m distance						
	Case 01 -NSBM 1		NSBM 2		Case 03 - Sunken	
Time	IGF1	BW1	IGF2	BW2	IGF3	BW3
01:00	25.86	25.94	25.19	25.27	27.58	27.70
02:00	25.77	25.79	24.96	25.06	27.48	27.62
03:00	25.62	25.69	24.89	24.92	26.24	26.34
04:00	25.76	25.86	24.48	24.58	26.32	26.55
05:00	25.98	26.03	24.10	24.21	26.33	26.56
06:00	26.54	26.63	24.26	24.41	27.50	27.70
07:00	28.65	28.74	27.06	27.28	28.28	28.40
08:00	31.46	31.52	29.14	29.53	29.03	29.25
09:00	31.65	31.93	30.25	30.58	30.64	30.89
10:00	31.94	32.44	30.83	31.28	31.25	31.58
11:00	32.31	32.84	31.97	32.45	31.96	32.54
12:00	32.34	32.88	32.09	32.65	33.08	33.68
13:00	32.54	33.15	32.36	32.92	33.25	33.88
14:00	32.63	33.12	32.25	32.95	32.55	33.21
15:00	31.53	31.94	31.57	32.18	32.28	32.87
16:00	30.23	30.61	29.42	29.88	30.65	31.24
17:00	29.21	29.57	28.59	28.95	30.48	31.06
18:00	28.86	29.20	28.06	28.31	30.06	30.34
19:00	28.40	28.62	27.46	27.67	30.00	30.28
20:00	27.94	28.15	27.02	27.25	29.62	29.94
21:00	27.41	27.52	26.53	26.77	29.54	29.86
22:00	27.05	27.12	26.14	26.32	28.94	29.05
23:00	26.67	26.76	25.78	25.95	28.55	28.75
24:00	26.10	26.18	25.35	25.42	28.14	28.25

Direct green facades

Outer wall						
	Case 01		Case 02		Case 03	
Time	Shaded Wall surface DGF1	Bare Wall surface BW1	Shaded Wall surface DGF2	Bare Wall surface BW2	Shaded Wall surface DGF3	Bare Wall surface BW3
01:00	28.21	28.38	26.18	26.24	25.26	25.47
02:00	27.47	27.81	26.06	26.25	25.23	25.36
03:00	26.21	26.7	25.43	25.9	25.76	26.05
04:00	26.49	26.81	25.34	25.85	25.95	26.37
05:00	26.61	26.92	25.75	26.31	26.37	26.83
06:00	27.54	28.43	26.53	27.55	27.08	27.84
07:00	28.72	29.925	27.55	29.67	28.48	30.37
08:00	28.61	30.64	28.62	30.88	28.37	31.09
09:00	28.38	32.23	29.88	32.77	28.14	32.68
10:00	29.27	34.88	30.15	34.78	29.03	35.33
11:00	30.62	36.38	32.13	36.32	30.38	36.83
12:00	32.15	38.24	32.24	37.45	30.91	37.69
13:00	32.64	38.42	32.75	38.67	31.39	38.87
14:00	32.08	39.38	32.48	37.13	31.84	38.83
15:00	32.27	38.84	32.48	36.44	31.98	37.55
16:00	31.48	37.86	32.38	35.72	31.24	36.31
17:00	30.98	34.53	31.30	33.8	30.74	33.98
18:00	30.36	33.52	30.00	31.04	30.12	32.97
19:00	29.65	31.74	29.85	30.16	29.61	30.19
20:00	29.44	31.51	29.54	29.86	29.38	29.64
21:00	29.14	30.58	29.30	29.58	28.91	29.12
22:00	28.84	29.85	29.30	29.44	28.49	28.6
23:00	28.64	30.16	28.45	28.56	27.39	27.46
24:00	28.46	28.95	27.40	27.44	26.22	26.27

10 Cm distance						
	Case 01		Case 02		Case 03	
Time	DGF1	BW1	DGF2	BW2	DGF3	BW3
01:00	28.19	28.28	25.75	25.83	25.23	25.32
02:00	27.66	27.74	25.53	25.68	24.5	24.59
03:00	26.8	26.89	25.42	25.51	24.23	24.45
04:00	26.69	26.94	25.76	26.08	24.8	24.95
05:00	26.9	27.18	25.96	26.21	25.24	25.61
06:00	27.27	27.62	26.33	26.82	28.34	28.67
07:00	28.54	29.3	28.98	29.69	29.52	30.13
08:00	29.85	30.82	29.94	30.68	30.21	31.16
09:00	30.61	31.86	31.15	32.48	30.98	32.34
10:00	31.64	32.87	32.40	33.64	32.06	33.63
11:00	32.29	33.58	33.30	34.65	33.21	34.57
12:00	32.34	33.96	33.25	35.05	33.45	34.96
13:00	33.61	35.11	33.58	35.24	33.83	35.21
14:00	34.23	35.65	33.60	35.12	33.76	35.25
15:00	33.94	35.25	33.34	34.74	33.61	35.05
16:00	33.11	34.5	33.45	34.48	33.12	34.52
17:00	32.45	33.29	32.15	33.16	32.57	33.69
18:00	31.01	31.81	31.58	32.48	31.45	32.54
19:00	30.49	30.95	30.08	30.50	30.95	31.5
20:00	30.16	30.41	29.25	29.55	30.54	30.81
21:00	30.13	30.28	29.18	29.46	29.13	29.36
22:00	29.23	29.35	28.83	29.12	27.25	27.35
23:00	28.96	29.08	28.3	28.54	26.37	26.45
24:00	28.75	29.24	27.54	27.68	25.42	25.48

1m distance						
	Case 01		Case 02		Case 03	
Time	DGF1	BW1	DGF2	BW2	DGF3	BW3
01:00	27.41	27.69	27.64	27.9	25.33	25.41
02:00	27.22	27.48	26.74	27.76	25.05	25.16
03:00	26.47	26.84	25.54	25.68	24.85	24.97
04:00	26.15	26.37	25.61	25.78	24.68	24.87
05:00	26.3	26.59	26.18	26.46	25.62	25.86
06:00	27.44	27.66	26.84	27.24	28.06	28.28
07:00	29.25	29.62	29.19	29.63	29.67	29.88
08:00	30.67	30.78	30.42	30.88	31.28	31.51
09:00	31.35	31.68	31.36	31.85	31.64	31.85
10:00	32.36	32.58	32.23	32.74	32.85	33.09
11:00	32.75	33	33.51	34.08	33.58	33.84
12:00	33.38	33.87	33.62	34.15	34.15	34.67
13:00	34.5	34.98	33.18	33.72	35.28	35.94
14:00	34.21	34.85	33.06	33.68	35.24	35.93
15:00	34	34.62	33.13	33.72	34.45	35.06
16:00	32.06	32.47	33.08	33.55	33.38	33.96
17:00	31.87	32.23	32.14	32.57	33.45	33.88
18:00	29.84	30.15	31.56	31.96	32.18	32.51
19:00	29.73	30.04	30.29	30.76	30.66	31.01
20:00	29.65	29.78	29.49	29.75	29.47	29.8
21:00	29.57	29.85	29.38	29.63	28.24	28.6
22:00	29.2	29.57	29.41	29.75	26.52	26.84
23:00	29.15	29.42	29.34	29.61	26.42	26.7
24:00	28.05	28.24	28.14	28.33	26.05	26.15

Temperature readings of the developed green panel

Time	Grass surface	1m front	Air gap	Adjacent wall surface	Wall surface behind panel	Internal wall surface	Internal temp.	Adjacent bare front	Shaded ambient temp.
12:00 AM	24.7	25.35	26.2	28.1	27.5	28.3	26.8	27.1	25.65
1:00 AM	24.2	24.65	25.5	27.45	27.15	27.95	25.95	26.5	24.55
2:00 AM	23.75	24.5	25	27	26.85	27.65	25.95	26.05	24.15
3:00 AM	23.15	24.2	24.8	26.5	26.35	27.3	25.3	25.55	24.2
4:00 AM	23	23.95	24.35	26.1	25.95	26.95	25.15	25.2	24.45
5:00 AM	22.7	23.7	24.25	25.7	25.65	26.7	24.7	24.75	23.7
6:00 AM	22.5	23.3	23.85	25.3	25.35	26.4	24.4	24.4	23.75
7:00 AM	22.65	23.3	23.6	25.2	25.1	26.05	24.25	24.2	23.15
8:00 AM	24.3	24.75	24.55	25.95	25.2	25.95	24.95	25	24.5
9:00 AM	26.6	27.35	26.4	30.55	25.6	26.2	26.35	26.55	26.7
10:00 AM	27.65	28.6	27.6	33.15	26.2	26.5	27.75	27.7	27.5
11:00 AM	30.45	31.25	29.3	36.55	27.15	27.2	29.2	29.4	29.25
12:00 PM	32.4	31.7	30.3	38.4	28.05	27.85	30.65	31.05	31.7
1:00 PM	36.35	33	31.7	40.95	28.85	28.25	31.2	32.9	33
2:00 PM	30.65	32	31.25	36.55	29.2	28.6	31	32.65	32.05
3:00 PM	29.4	30.35	30.35	34.5	29.35	28.75	30.15	31.85	30
4:00 PM	28.3	29.15	29.35	33.05	29.15	28.7	29.2	30.65	28.5
5:00 PM	27.75	28.6	28.75	31.9	28.85	28.8	28.9	29.9	28.35
6:00 PM	26.55	27.75	27.9	30.4	28.5	28.6	28.2	28.95	27.65
7:00 PM	26.1	27.25	27.8	29.6	28.3	28.45	27.8	28.3	26.8
8:00 PM	25.5	27.15	27.35	28.95	28	28.2	27.5	27.85	26.9
9:00 PM	24.95	26.45	27.05	28.3	27.7	27.95	27	27.4	26.35
10:00 PM	24.6	25.85	26.35	27.85	27.4	27.7	26.6	26.85	25.65
11:00 PM	23.95	25.25	25.6	27.2	26.8	27.4	25.85	26.2	25.2

Temperature readings of the developed modular panel green wall

Time	Grass surface	1m front	Air gap	Adjacent wall surface	Wall surface behind panel	Internal wall surface	Internal temp.	Adjacent bare front	Shaded ambient temp.
12:00 AM	24.4	25.3	25.7	27.9	27.4	28.3	26.4	26.95	25.5
1:00 AM	24.25	24.55	25.35	27.35	27.1	27.9	26.15	26.45	24.25
2:00 AM	23.8	24.35	25.1	26.95	26.75	27.5	25.85	26.1	23.95
3:00 AM	23.1	24.1	24.55	26.3	26.25	27.2	25.1	25.35	24.4
4:00 AM	22.9	23.9	24.3	26	25.9	26.9	25.05	25.1	23.9
5:00 AM	22.75	23.6	24.2	25.6	25.6	26.55	24.65	24.65	23.6
6:00 AM	22.5	23.3	23.55	25.2	25.2	26.25	24.4	24.25	23
7:00 AM	23.35	23.85	24	25.45	25.05	26.05	24.55	24.45	23.65
8:00 AM	24.85	25.85	25	26.65	25.25	25.95	25.3	25.45	25.65
9:00 AM	26.8	27.5	26.85	31.5	25.75	26.2	27.05	26.9	26.9
10:00 AM	28.75	29.65	27.85	35	26.55	26.65	28.1	28.25	29.6
11:00 AM	31.7	31.5	30.4	37.6	27.4	27.4	30.45	30.1	31.65
12:00 PM	33.15	32.7	30.9	38.4	28.25	27.9	31.2	31.55	31.6
1:00 PM	31.05	31.4	31.2	40.25	28.95	28.45	31.6	33.65	32.1
2:00 PM	30.05	31.25	30.95	35.65	29.45	28.75	30.6	32.35	31.05
3:00 PM	29.1	30.5	30.15	33.85	29.3	28.75	29.65	31.45	30.15
4:00 PM	31.8	29.25	29.3	33.35	29.05	28.75	29	30.35	28.55
5:00 PM	27.2	28.2	28.65	31.3	28.75	28.75	28.7	29.6	27.8
6:00 PM	26.4	27.45	27.75	30.05	28.35	28.55	28	28.7	27.15
7:00 PM	26.1	27.1	27.45	29.45	28.2	28.4	27.8	28.15	26.7
8:00 PM	25.35	27.05	27.15	28.75	27.95	28.2	27.45	27.7	26.55
9:00 PM	24.75	26.45	26.6	28.1	27.45	27.9	26.8	27.1	26.05
10:00 PM	24.25	25.65	26.05	27.6	27.2	27.7	26.2	26.6	25.75
11:00 PM	23.65	25	25.45	27	26.65	27.3	25.8	26	24.9

Appendix D: Constant head permeability calculation tables

Calculation Table - for 1:0 Ratio						
S/W	h1 (m) x 10^{-2}	h2 (m) x 10^{-2}	Δh (m)x 10^{-2}	V m^{-3}	Time (sec)	Rate of Flow m^3/s
1	70.5	100	29.5	1 x 10^{-3}	45.16	2.21 x 10^{-5}
2	66.6	96.8	30.4	1 x 10^{-3}	48.09	2.079 x 10^{-5}
3	63.6	93	29.4	1 x 10^{-3}	48.81	2.048 x 10^{-5}
4	60.8	89.1	28.01	1 x 10^{-3}	50	2.0 x 10^{-5}
5	57.8	85.5	27.7	1 x 10^{-3}	50.42	1.983 x 10^{-5}
6	55.3	81.8	26.5	1 x 10^{-3}	51.28	1.95 x 10^{-5}
7	52.9	78.7	25.8	1 x 10^{-3}	52.34	1.91 x 10^{-5}
8	49.5	75.1	25.6	1 x 10^{-3}	53	1.88 x 10^{-5}

Calculation Table - for 1:1 Ratio						
S/W	h1 (m) x 10^{-2}	h2 (m) x 10^{-2}	Δh (m)x 10^{-2}	V m^{-3}	Time (sec)	Rate of Flow m^3/s
1	73.3	100	26.7	1 x 10^{-3}	50.6	1.976 x 10^{-5}
2	71.4	97.5	26.1	1 x 10^{-3}	51.8	1.930 x 10^{-5}
3	69.4	95.3	23.9	1 x 10^{-3}	52.47	1.905 x 10^{-5}
4	67.3	92.7	25.7	1 x 10^{-3}	52.78	1.894 x 10^{-5}
5	65.2	90.3	25	1 x 10^{-3}	53.57	1.866 x 10^{-5}
6	62.7	87.4	24.7	1 x 10^{-3}	53.91	1.835 x 10^{-5}
7	60.7	84.9	24.2	1 x 10^{-3}	55.65	1.796 x 10^{-5}
8	58.8	82.4	23.6	1 x 10^{-3}	56.28	1.776 x 10^{-5}

Calculation Table - for 1:2 Ratio						
S/W	h1 (m) x 10^{-2}	h2 (m) x 10^{-2}	Δh (m)x 10^{-2}	V m^{-3}	Time (sec)	Rate of Flow m^3/s
1	75.9	100	24.1	1 x 10^{-3}	48.28	2.07 x 10^{-5}
2	74.1	97.2	23.1	1 x 10^{-3}	49.03	2.039 x 10^{-5}
3	72.2	95.3	23.1	1 x 10^{-3}	50.16	1.98 x 10^{-5}
4	70.3	92.9	22.6	1 x 10^{-3}	50.44	1.982 x 10^{-5}
5	68.4	90.7	22.3	1 x 10^{-3}	51.31	1.948 x 10^{-5}
6	66.6	88.6	20	1 x 10^{-3}	51.88	1.927 x 10^{-5}
7	64.9	86.4	21.5	1 x 10^{-3}	52.25	1.913 x 10^{-5}
8	63.1	84.2	21.1	1 x 10^{-3}	52.94	1.888 x 10^{-5}
9	61.3	82.1	20.8	1 x 10^{-3}	53.4	1.87 x 10^{-5}

Calculation Table - for 1:3 Ratio						
S/W	h1 (m) x 10^{-2}	h2 (m) x 10^{-2}	Δh (m)x 10^{-2}	V m^{-3}	Time (sec)	Rate of Flow m^3/s
1	85	100	15	1 x 10^{-3}	49.97	2.0 x 10^{-5}
2	81	94	13	1 x 10^{-3}	50.48	1.98 x 10^{-5}
3	78.2	91.9	13.7	1 x 10^{-3}	50.82	1.967 x 10^{-5}
4	76.5	89.5	13	1 x 10^{-3}	51.82	1.92 x 10^{-5}
5	74	87.1	13.1	1 x 10^{-3}	51.9	1.92 x 10^{-5}
6	72.5	84.1	12.1	1 x 10^{-3}	52.47	1.93 x 10^{-5}
7	70.3	82.1	11.8	1 x 10^{-3}	52.75	1.89 x 10^{-5}
8	68.1	80.1	12	1 x 10^{-3}	53.09	1.88 x 10^{-5}
9	66.5	78.2	11.7	1 x 10^{-3}	54.22	1.84 x 10^{-5}
10	65	76.1	11.1	1 x 10^{-3}	54.69	1.82 x 10^{-5}

Calculation Table - for 1:4 Ratio						
S/W	h1 (m) x 10^{-2}	h2 (m) x 10^{-2}	Δh (m)x 10^{-2}	V m^{-3}	Time (sec)	Rate of Flow m^3/s
1	92.7	100	7.3	1 x 10^{-3}	47.56	2.10 x 10^{-5}
2	90.8	98.8	7.4	1 x 10^{-3}	47.96	2.08 x 10^{-5}
3	89.1	96.5	7.4	1 x 10^{-3}	48.62	2.05 x 10^{-5}
4	87.7	94.9	7.2	1 x 10^{-3}	49.18	2.03 x 10^{-5}
5	86.1	93.2	7.1	1 x 10^{-3}	49.51	2.01 x 10^{-5}
6	84.1	91.5	6.9	1 x 10^{-3}	50.09	1.99 x 10^{-5}
7	82.9	89.8	6.9	1 x 10^{-3}	50.44	1.98 x 10^{-5}
8	81.4	88.3	6.9	1 x 10^{-3}	51.06	1.96 x 10^{-5}
9	79.9	86.6	6.7	1 x 10^{-3}	51.28	1.95 x 10^{-5}
10	78.4	84.9	6.5	1 x 10^{-3}	51.68	1.93 x 10^{-5}

Appendix E: Field data collection sample for simulation studies

System's average end use details

System / Equipment	Detail category	Operating hours	Energy use (W/m^2)
Cooling system	Air-conditioned	08.00 am- 04.30 pm	75
Ventilation system	Standard	08.00 am- 04.30 pm	5
Lighting	T8 - Fluorescent	08.00 am- 04.30 pm	15
Office equipment	Standard	08.00 am- 04.30 pm	15
Other appliances	Standard	08.00 am- 04.30 pm	5

Physical characteristics of base model building

Characteristics / components	Description of the base model
Location	Colombo, Sri Lanka. Latitude – 6° 54', Longitude – 79° 52'
Type & shape of building	Eight stories, office building, narrow rectangular
Total height	29.2m
Typical floor height	3.25m
Floor dimensions (typical)	Total floor = 23m x 10m Office space = 17m x 10m
Gross floor area	$1590m^2$ (ceramic tiles)
External wall	Brick double leaf (225mm), 20mm plaster
Internal floors	16mm Gypsum board, 25mm airspace and 16mm Gypsum board
Roof	200mm RC dense with 20mm bitumen outside layer
Glazing	Single pane, single clear/no shading 6mm, U = 6.121 W/m^2k. total solar transmission (SHGC) = 0.81, direct solar transmission = 0.775, light transmission = 0.881
Number of occupants	245
Lighting	15 W/m^2
Type of lighting	T8 - Fluorescent
Computers & equipment	15 W/m^2
Other appliances	5 W/m^2
HVAC system	Constant air volume, total no. of AHU's = 8 each AHU power ratings = 31.85kW, no of zones = 8
Set point temperature	24°C – 26°C

Occupancy pattern of the building & details of equipment and light fittings

Floor	Units of areas occupied	Total occupied area(m^2)	No: of occupants	Occupants density
Ground floor	Parking	160.78		
Mezzanine	CESL & Maintenance	95.57	27	5.16
First floor	C & QS P & C	69.6 69.6	12 13	5.8 5.35
Second floor	AGM(Projects)	139.2	15	9.28
Third floor	IT	139.2	20	6.96
Fourth floor	Water resources	139.2	18	7.73
Fifth floor	Architectural	139.2	18	7.73
Sixth floor	Internal audit Government audit	69.6 69.6	17 6	4.06 11.6
Seventh floor	Functional Hall	174	100	1.74
Machine floor	Machine floor	156.02	1	156.02
Roof top	Machine floor	156.02	1	156.02

floor	A/C unit		Light fittings		computers	other
	Type	units	Type	No:		
Ground floor	-	-	CFL (7W)	16	-	-
Mezzanine	24 BTU	3	T5 fixtures CFL (7W)	12 02	25	Printers 01 Copiers 01
First floor	31.85kW AHU	1	T5 fixtures CFL (7W)	20 03	15	Printers 02 Copiers 01
Second floor	31.85kW AHU	1	T5 fixtures CFL (7W)	20 06	20	Printers 02 Copiers 01
Third floor	31.85kW AHU	1	T5 fixtures CFL (7W)	20 06	20	Printers 02 Copiers 01
Fourth floor	31.85kW AHU	1	T5 fixtures CFL (7W)	28 06	18	Printers 03 Copiers 01
Fifth floor	31.85kW AHU	1	T5 fixtures CFL (7W)	28 06	24	Printers 04 Copiers 02
Sixth floor	31.85kW AHU	1	T5 fixtures CFL (7W)	30 06	-	-
Seventh floor	22kW fan coils	3	T5 fixtures CFL (7W)	28 06	-	
Machine floor	98.9 kW AHU	1			-	
Roof top					-	