THERMAL PERFORMANCE IMPROVEMENT FOR RESIDENTIAL BUILDINGS IN THE TROPICS THROUGH THE APPLICATION OF GREEN FAÇADE AND GREEN ROOF

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“I like to think that I took the sourest lemon that life has to offer and turned it into something resembling lemonade.”

Dan Fogelman

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ABSTRACT

Green envelope strategies are a passive cooling technique adopted to lessen surfaces temperature due to the heat capacity storage of vegetation lower than the other structure materials. This research assesses the green façades and green roofs to rate heat transfer through building envelopes and cooling load. The research used the Overall Thermal Transfer Value (OTTV) index to calculate the thermal performance of selected case studies and developed computational workflows. Moreover, the Green Building Studio simulated the annual energy consumption through bare and vegetated envelopes scenarios. Three tropical species climbers, Hedera Helix, AntigononLeptopus, and Lonicera Japonica, were chosen to assess the thermal impact of a green façade applied to a bare opaque wall. In comparison, the green roof's lawn was limited to a single variety (Cow grass). The results indicated that the Hedera Helix climber's thermal performance was superior to the other climbers. The implementation of green façade and green roof reduced OTTV and steady-state heat gain of roofs of case study buildings by 19 % and 90%, respectively. Thus, the overall annual and monthly energy consumption reduction achieved by 11% and 14%, respectively; in parallel, the annual carbon dioxide (CO_2) emissions from energy consumption dropped to 13%. On the other hand, the correlation between the annual cooling loads and corresponding OTTV for residential buildings revealed a strong relationship between the annual cooling load and the OTTV amount. Regarding the validation of the developed OTTV computational workflow, it was found that tolerance between the proposed systems and the manual calculation is approximately 0% to 2.17 % within the acceptable range. In conclusion, green facades and roofs help reduce the U-value of the building's envelope, reduce heat transfer and lower cooling loads, carbon dioxide (CO_2), and electricity costs. A simple and flexible approach to calculating the total heat transfer value (OTTV) and the proposed U-value with little human error and immediate results when determining the average heat transfer into a building.

ABSTRAK

Strategi sampul hijau adalah teknik penyejukan pasif yang digunakan untuk mengurangkan suhu permukaan kerana penyimpanan haba oleh tumbuh-tumbuhan lebih rendah daripada penyimpanan haba oleh bahan binaan. Dalam penyelidikan ini, fasad dan bumbung hijau dikaji untuk menilai pemindahan haba melalui sampul bangunan dan beban penyejukan. Penyelidikan menggunakan indeks Nilai Pemindahan Termal Keseluruhan (OTTV) untuk mengira prestasi termal bagi kajian kes yang dipilih dan seterusnya mengembangkan aliran kerja secara simulasi. Kemudian daripada itu, dengan menggunakan aplikasi Green Building Studio penggunaan tenaga tahunan melalui senario sampul kosong dan tumbuhan memanjat disimulasikan. Tiga spesies tumbuhan memanjat tropika seperti, Hedera Helix, Antigonon Leptopus, dan Lonicera Japonica, dipilih untuk menilai kesan terma dari fasad hijau yang diterapkan pada dinding legap. Sebagai perbandingan, rumput bumbung hijau terhad kepada satu jenis (rumput lembu). Hasil kajian menunjukkan bahawa prestasi termal tumbuhan memanjat Hedera Helix lebih unggul daripada pendaki lain. Pelaksanaan fasad dan bumbung hijau dalam mengurangkan nilai pemindahan haba keseluruhan (OTTV) dan peningkatan haba bumbung bangunan bagi kajian kes masing-masing ialah sebanyak 19% dan 90%. Oleh itu, pengurangan penggunaan tenaga tahunan dan bulanan secara keseluruhan dicapai masing-masing sebanyak 11% dan 14%; selari dengan pembebasan gas karbon dioksida (CO_2) tahunan dari penggunaan tenaga, menurun kepada 13%. Sebaliknya, hubungan antara beban penyejukan tahunan dan nilai pemindahan haba keseluruhan (OTTV) yang sesuai untuk bangunan kediaman menunjukkan hubungan yang kuat antara beban penyejukan tahunan dan jumlah nilai pemindahan haba keseluruhan(OTTV). Mengenai pengesahan aliran kerja komputasi nilai pemindahan haba keseluruhan (OTTV) yang dikembangkan, didapati bahawa toleransi antara sistem yang dicadangkan dan pengiraan secara manual adalah sekitar 0% hingga 2.17% iaitu dalam julat yang dapat diterima. Kesimpulannya, fasad dan bumbung hijau membantu mengurangkan nilai-U sampul bangunan, mengurangkan pemindahan

haba dan menurunkan beban penyejukan, pembebasan gas karbon dioksida (CO_2), dan kos elektrik. Pendekatan sederhana dan fleksibel untuk pengiraan nilai pemindahan haba keseluruhan (OTTV) dan nilai-U yang diusulkan dengan kesalahan manusia yang sedikit dan hasil segera apabila menentukan pemindahan haba purata ke dalam sebuah bangunan.

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API	-	Application Programming Interface
ASEAN	-	Association of South East Asian Nations
ASHRAE	-	The American Society of Heating, Refrigerating and Air Conditioning Engineers
AL	-	Antigonon Leptopsus
BIM	-	Building Information Modelling
BC	-	Before Christ
CBEC	-	Commercial Buildings Energy Consumption
CIBSE	-	Chartered Institution of Building Services Engineers
CO_2	-	Carbon Dioxide
DOE	-	Department Of Energy
DSF	-	Double Skin Façade
3D	-	Three Dimensional
2D	-	Two Dimensional
Ec	-	Annual cooling energy consumption
ETTV	-	Envelope Thermal Transfer Value
GBS	-	Green Building Studio
GBI	-	Green Building Index
GreenRE	-	Green Real Estate
GRT	-	Green Rating Tool
HVAC	-	Heating, Ventilation and Air Conditioning
HH	-	Hedra Helix
LAI	-	Leaf Area Index
LJ	-	Lonicera Japonica
OF	-	Solar orientation factor, Wall/ Roof
OTTV	-	Overall Thermal Transfer Value of building envelope

$OTTV_i$	-	Overall Thermal Transfer Value at a given orientation
$OTTV_c$	-	Overall Thermal Transfer Value compute system
$RTTV$	-	Roof Thermal Transfer Value
SC	-	Shading Coefficient of window glass/ Shading coefficient of the skylight
SC_1	-	Effective Shading Coefficient of the glass
SC_2	-	Effective Shading Coefficient of the shading device
SF	-	Roof solar factor
WWR	-	Window to Wall Ratio
VPL	-	Visual Programming Language

Nomenclature

A	-	Total wall area
A_o	-	Gross roof area
A_1	-	The gross exterior wall area for orientation 1
A_f, A_w	-	Wall and window area
A_R	-	Opaque roof area
A_{Ra}	-	Respective area of different roof sections
A_S	-	The area of the skylight
α	-	Solar absorptivity of the opaque wall
ΔT	-	The temperature variance between exteriors and interiors condition
Qgc	-	Heat conduction through window glass
Qgs	-	Solar heat gain through window glass
Qwc	-	Heat conduction through the opaque wall
TD_{eq}	-	Equivalent Temperature Difference
U_w, U_f	-	U–value of walls and window
U_r	-	The thermal transfer value of the opaque roof
U_{rn}	-	Thermal transmittance of different roof sections
U_S	-	Thermal transmittance value of window glass

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The purpose of this thesis is to examine the potential of green façade and green roof technologies in the Malaysian building industry to lower the Overall Thermal Transfer Value (OTTV) of residential buildings and thereby lower energy consumption. This chapter discusses the research background, problem statement, questions and hypothesis, aims, techniques, scopes and limitations, significance, and thesis structure.

1.2 Research background

This research will examine several strategies for boosting the energy efficiency of buildings. As a result, this section will discuss energy-efficient tactics and their relationship to energy efficiency improvement. Following that, a brief discussion of energy-efficient methods and their relationship to current research was held.

1.2.1 The global scenario for building energy use

In recent years, energy efficiency in buildings has gained popularity due to increased concern about CO_2 and other greenhouse gas (GHG) emissions and the shortage of fossil fuels. Energy demand is intimately related to the building and construction sectors. Buildings consume an astounding 40% of global energy. For instance, if the energy required to manufacture steel, cement, aluminium, and glass for building construction is included, this consumption may exceed 50% (Energy Efficiency in Buildings, 2009). Thus, buildings may play a critical part in the transition to a sustainable society, which is why initiatives to increase building efficiency have been pushed.

1.2.2 Building energy efficiency and energy-efficient approaches

The energy efficiency is measured in kilowatt-hours per square meter of floor space or envelope area per year (KWh/m^2/year); given the country's climate, each building style has its benchmark for energy efficiency (Hassan, 2013). The benchmarks help assess a building's energy efficiency and identify key performance indicators for improvement. Whereas the energy efficiency of building envelope materials is critical when calculating cooling and heating requirements. Therefore, two codes were created to improve the airtightness and thermal insulation of building envelopes: the thermal insulation standard (U-value) for cold climates and the Overall Thermal Transfer Value (OTTV) code for South Asian climates. Both codes set minimum standards for thermal insulation and energy efficiency.

Furthermore, passive cooling techniques such as louvre shading devices, double glazing, natural ventilation, active vegetation, insulation, evaporative cooling via a fountain, and high-reflective light colour coatings have demonstrated their ability to increase the efficiency of buildings and minimise environmental impacts related to energy. The emergence of energy conservation as a critical issue has sparked a search for a feasible method of increasing building energy efficiency (Santamouris, 2013). As a consequence, numerous passive solutions have been identified as potential options for improving Malaysia's energy performance, including active vegetation in the form of a green wall (Basher, 2019), a green roof (Juliet *et al*., 2016), and a courtyard (Taib *et al.*, 2010).

1.2.3 Eleventh Malaysia plan and present research

Malaysia's government has imposed a plan entitled "Malaysia 11th plan" since 2016. A component of this strategy is to optimize energy use by promoting low-carbon mobility and green buildings concept. Thus, all new government buildings must be energy efficient. The 11th plan aimed to improve new building performance by incorporating green features, materials, and designs into commercial and residential buildings. Moreover, the plan also promotes green design and insulation materials for old buildings. According to the Malaysia Ministry of Economic Affairs (MMEA), by 2030, the 11th plan aims to reduce GHG emissions by 45 per cent (MMEA, 2015). Therefore, measurements to improve GHG reduction in transportation, industry, and buildings have been promoted.

The commercial and residential sectors have the third-highest energy requirements across all other sectors in 2012 (12.8%) (Ponniran *et al.*, 2012). This amount is expected to rise in the future based on Malaysia's existing needs. Buildings consumed 49.5% of Malaysia's electricity in 2018. The residential sector consumes half of that per cent mostly to run air conditioners and other equipment (Energy Commission, 2018). Abass *et al.* (2016) and Abass *et al.* (2021) investigated how passive cooling (courtyard) might reduce energy consumption and CO_2 emissions in commercial buildings, particularly office buildings. Thus, the current study builds on the 2016 study by boosting the thermal performance of residential structures with green roofs and green façade passive cooling strategies.

Green envelopes have recently been investigated globally for their thermal performance (Dahanayake & Chow, 2019), ability to reduce the effect of the Urban Heat Island (UHI) (Di Giuseppe & D'Orazio, 2015; Victorero *et al.*, 2015), and ability to reduce the cooling load for the building interior (De Masi *et al.*, 2019; Wahba *et al.,* 2018). In Malaysia, green façades and green roofs on commercial and residential buildings have been studied for passive cooling. Thus, validating the green systems' mechanism has become a top research priority. Several studies examine the ability of vertical green systems, such as a green façade or living wall, to reduce indoor air temperature (Basher, 2019; Ismail, Samad, & Rahman, 2011; Jaafar *et al.*, 2013; Khairul *et al.*, 2013; Safikhani *et al.*, 2014), the energy efficiency of green roofs and green walls (Azis *et al.*, 2019), and the ability of green roofs to mitigate CO_2 (Arabi *et al.*, 2015; Ismail *et al.*, 2012).

Most of the research cited previously used field tests and an experimental lab to test green technologies on existing buildings. These findings are useless to designers and engineers tasked with implementing and measuring the success of green solutions. In Malaysia, studies that provided the method for green systems by determining the thermal transmittance coefficient using mathematical models based on the thermal attributes of each component are still limited. As a result, the current research aims to close a knowledge gap by developing an efficient and reliable approach for calculating the thermal performance of green envelopes using data from a system's design.

For the annual thermal performance of the case studies, the OTTV was selected as the energy performance index. It should be noted that the index was introduced in 1991 voluntarily. Architects and designers used to manually calculate parameters for complex building layouts using Excel sheets or estimation tools. A system for estimating the OTTV has been proposed in several studies using BIM and the Visual Programming Language (Lim *et al*., 2016, Seghier *et al*., 2017). Therefore, the research provides methods for calculating (OTTV) and Roof Thermal Transmittance Values (RTTV).

1.3 Problem statement

In Malaysia, the high electricity demand has extended the residential buildings' energy consumption to meet growing economic, ecological and social impacts (Hassan & Hafeez, 2017). Consequently, the residential sector shared 20.3 GWh of the total national percentage in 2018, even though it is ranked third after the industrial and commercial sectors. While most residential buildings' external wall was constructed using precast concrete and concrete blocks by 50% and 25%, respectively. Whereas 36 and 30 per cent for prefabricated steel and trusses, respectively used for roof construction (Ee & Danesh, 2016). These materials worked as storage of the heat during the day and released it during the night, making the residents tend to experience the source of discomfort, especially during the night (Kubota, Toe, & Chyee, 2016). According to Toe (2013), the high thermal mass of the building envelope of a residential building could be challenging to be cooled at night under the hot-humid climate, especially during the nighttime of urban heat islands.

On this account, to achieve the indoor comfort range in the residential sector, the majority of dwellings are occupied with air conditioning units; Saidur, Masjuki, and Jamaluddin (2007) mentioned that the number of households with an air conditioning system in 1999 was found to be 493,082, which grew to 775,000 units in 2000 and by approximately reached to almost million units in 2009. The average operation hours by air conditioning is up to 12 hours (Hisham *et al*., 2020). According to the Department of Statistics Malaysia (2020), the energy sharing percentage of Malaysian residential buildings has increased to 35.360 GWh, and CO_2 emissions are expected to rise to 11,689,308 tons by 2020 (Bari *et al.,* 2012), with the majority of the increase of energy demand related to the cooling load. Al-Mofeez (2007) stated that the opaque envelopes of retrofitting buildings, especially residential buildings, contribute between 30-45 per cent to the cooling load. Therefore, implementing the proper thermal insulation will reduce energy demand and increase thermal comfort through energy-efficient designs. According to Castleton *et al*. (2010), energy-efficient designs like passive cooling strategies progressively reduce energy usage.

However, the works of Al Obaid (2004), Kubota *et al*. (2016), Toe (2013a) and Zakaria, Kubota, and Toe (2015) represent examples of a continuous exploration of different passive cooling strategies to mitigate energy use and ensure thermal comfort efficiency. Similarly, the studies of Basher (2019), Azis *et al*. (2019), and Juliet *et al.* (2016) on green envelopes support the claim that green façade and green roofs can substantially reduce cooling load and improve building thermal performance.

Therefore, this research establishes the relationship between a green façade and a green roof as a passive cooling technique with an energy code, i.e., OTTV, is under-investigated. This research adopted two techniques to achieve the research aims using the OTTV formula suggested by MS1525 and the energy simulation cloud. The investigation was conducted in three residential buildings in Johor Bahru, Malaysia, to highlight the green envelopes' potential for reducing OTTV amount and energy consumption.

1.4 Research questions and hypothesis

Researchers debate the use and efficiency of green envelopes in the Malaysian context; the underlying assumption is that buildings with a green façade and roof will perform better thermally than buildings with an opaque façade and roof. Besides that, it is critical to consider the difficulty of manually calculating the OTTV using the MS1525:2014 formula during the design stage or as part of the authority's criteria for green envelopes in buildings using the old methodology, i.e., manual computation. As a result, the research question that serves as the primary focus is as follows:

Does adding a green façade and a green roof into building envelopes reduce OTTV, lowering energy consumption? The following driving-related issues will be discussed in order to provide an answer to the primary question:

i. What will be the effect of the inclusion of green envelopes on heat transmittance into the buildings?
ii. What would impact a green façade and a green roof on OTTV's value for buildings in the tropics?
iii. How much energy can be saved annually from green façade and green roof applications?
iv. What is the impact of providing a new technique for OTTV calculation on time-saving during building thermal performance analysis?

Therefore, this thesis hypothesizes that calculating OTTV with the formula given in the Malaysia Standard (MS1525:2014) for building incorporated with a green façade and a green roof will result in a reduction of OTTV; also, the reduction of the energy consumption for operating air-conditioning, CO_2 emissions, and energy cost-saving will achieve.

1.5 Research objectives

The purpose of this research is to delve deeper into the ongoing debate over the use of green envelopes in Malaysia by examining and evaluating the effect of green façades and green roofs on solar heat transfer into buildings.
Additionally, the research has the following specific objectives:

(i) To develop a series of workflows to calculate OTTV and U_r of Malaysian buildings using BIM and VPL.
(ii) To evaluate the impact of a green façade and a green roof on heat transmittance and OTTV.
(iii) To analyse the annual energy, CO_2 emissions, and cost-saving in building electricity due to utilization of a green façade and green roof.

1.6 Methodology

Six phases of research were conducted. The first phase entails developing a methodology for computing the OTTV and U_r using BIM and VPL. The created workflow was then validated on theoretical and existing case studies using a traditional technique and the Building Energy Intensity Tool (BEIT) to ensure practicality and dependability. After that, data on residential buildings, suitable green systems, plants used in green systems, heat gain parameters of residential buildings, air conditioning systems, and 2D drawings of selected case study buildings were collected from credible sources (consultancy firm and literature).

The third phase involved developing workflows based on the MS1525:2014 equations, namely OTTVc and U_r, and utilising BIM and VPL to quantify the steady-state heat gain of the wall and roof in variance residential buildings. Following validation of the proposed workflows, mathematical modelling was used to estimate the thermal transmittance coefficient for opaque walls and roofs and green façade and green roof applications. The fourth phase involved entering all of the obtained data for the building's walls, windows, and green systems into the authoring BIM tool (i.e., Revit Architect). The fifth phase involved computing the OTTV of walls and U_r for several scenarios, including baseline design, semi-coverage, and full coverage. The second and third scenarios included the implementation of green systems in the case studied façades. After completing the preceding steps, the annual energy consumption of case studies was computed using the Green Building Studio (GBS) cloud. An annual space cooling energy, CO_2 emissions, and annual electricity cost were estimated using mathematical formulas and Excel spreadsheets due to the energy simulation.

The six steps illustrated the findings of a study into the thermal performance of building walls covered in green facades, either entirely or partially. Following that, we examined the expected thermal performance of the building's walls and roof. The heat gain and energy performance were calculated using the OTTV formula and energy simulation, and annual energy, CO_2 emissions, and electricity cost savings were calculated, analysed, and visualised using Origin Lab software. Additionally, a correlation between the OTTV value and annual space cooling energy consumption has been established to validate the OTTV value and establish a baseline value for energy management. It is worth noting that the roof heat gain was included in an integrated building heat gain calculation to ensure accurate results of cooling energy consumption.

1.7 Research scopes and limitations

The majority of the reviewed literature highlights multiple compelling reasons for using green envelopes in the Malaysian environment, most notably in thermal comfort and performance potential (Safikhani & Baharvand, 2017, Jaafar *et al*., 2013). The recently finished Le Nouvel Condominium building in Kuala Lumpur and Heriot-Watt University Malaysia witness to this. As a result, it is necessary to provide designers with a mechanism for determining the thermal transmittance value of this sort of façade and roof. Therefore, this study investigates the influence of green envelopes, more precisely an indirect green façade and a lightweight extensive green roof, on the OTTV of existing buildings in Malaysia's climate.

This study's thermal performance evaluation and analysis are focused on the quantity of heat conduction through two different types of building envelopes: opaque and green. While numerous variables can affect solar heat transmission through building components, this research focuses on heat conduction through façade with and without green envelopes on two and four orientations of the case study buildings. Apart from solar heat transmission, the effect of wall and roof heat conduction thru a green façade and a green roof on cooling capacity and corresponding OTTV is also examined by comparing the results using the chosen simulation tool. However, this thesis does not address heat conduction through windows or solar heat gains through glass windows concerning overall solar heat transmission in the selected case studies. The time of the mechanical operating is consistent in all simulated scenarios for daily, monthly, and annual energy consumption, which is considered between 6:00 pm and 6:00 am.

A simple layout design of three unique residential buildings (bungalow houses) was chosen to estimate solar heat transmission through building envelopes. Compared to the basic scenario, energy and OTTV analyses of the green façade and green roof cases are conducted and discussed. While there is no application of green envelopes in real case studies, the system's components of a green façade and an extensive green roof will be modelled using the BIM authoring tool (Revit

Architecture). The base model of green envelopes is intended to reproduce Holm's (1989) model. The OTTV formula is the one that MS1525 recommends for commercial buildings equipped with air conditioning. Additionally, all thermal and physical properties of construction materials not specified in (MS 2680, 2017) are derived from preliminary studies and standards undertaken in regions with similar climate conditions to Malaysia.

1.8 Research significance

This research will demonstrate the potential effect of the green envelopes on reducing the building's cooling load and reducing the measured OTTV. The research will also provide a way to estimate the thermal transmission value for green envelopes that can be selected for easy calculation of the OTTV by professionals designing green envelope buildings as needed in the Malaysian Standard (MS1525, 2014).

The research findings will add value to Malaysia's current building design standard related to green envelope-integrated construction. This objective would participate towards accomplishing the Malaysian plan towards sustainable development as suggested by the Malaysia Ministry of Economic Affairs (MMEA, 2015). Moreover, this research output is expected to benefit building authorities charged with developing or improving existing building energy standards to increase energy efficiency and other construction professionals charged with submitting construction documents to the approving authority.

Finally, this research will benefit architects and engineers responsible for analysing the building thermal performance and making decisions regarding energy performance during preliminary design stages. This proposed workflow will be increased the designer's capability and direct accessibility to check and modify the material's thermal properties to enhance the envelope's performance during design stages without any practitioners' technical expertise requirements in BIM and VPL.

1.9 Thesis structure

The outline of this research is presented in this section. This thesis comprises six chapters. It includes the introductory chapter. The detailed elements of this research are as follow:

(i) **Chapter 1: Introduction:** This chapter discusses the research background, problem statement, questions and hypothesis, aims, techniques, scopes and limitations, significance, and thesis structure.

(ii) **Chapter 2: Literature Review:** The chapter defines the detail of the strategies environmental in a tropical climate and describes the environmental design condition over several sections. Section one starts with a literature review of the two types of vegetation (green facade and green roof) definition and their implementation of this research. Furthermore, green systems' potential to alleviate the air temperature through simulation and experimental-based research locally and worldwide is critically reviewed. The second section outlined the mechanism of the heat and mass transfer of the building envelope, and it has been demonstrated the model of the green systems provides by previous scholars regarding the reduction of heat transfer. Section three and four explained the theory of Overall Thermal Transfer Value (OTTV) and highlighted the adaption of OTTV as an indicator to calculate the heat gain through the building exterior. Moreover, BIM and VPL's integration of simulated building and energy performance is highlighted during building design or decision-making.

(iii) **Chapter 3: Research methodology:** This chapter is set to design the overall methodological process required for this research in the computation approach. It presents the methods, approach, strategy and research procedure, theory, and computation method. It then goes on to provide the criteria used for selecting the green system through extensive review and simulation from previous studies are also discussed. Moreover, the selected green wall and green roof's model design was highlighted in detail, while an extensive review of all the thermal properties parameters of case studies construction materials and the green façade and green roof from literature review and standard were obtained in this chapter.

(iv) **Chapter 4: Development of OTTV computational workflows:** This chapter brings together the first approach adopted throughout this research methodology. There are two types of research methods undertaken in this research: the computation of OTTV using BIM and VPL concepts and the energy simulation. This chapter describes and discusses the methods used in workflow development. It then describes the workflow and the validation technique adopted in the research in greater detail. This chapter's primary purpose is to verify the OTTV workflow's effectiveness since it is easy to run and requires least knowing the VPL tool.

(v) **Chapter 5: Results and discussion:** The main findings of the OTTV and energy simulation on the case studies with and without the green façade based on several scenarios are presented in this chapter. To extend the chapter, including the verification of the OTTV and the energy simulation results to link OTTV and energy consumption reduction after covering the case studies with the green envelope. Besides, the result of the reduction of CO_2 and the electricity cost. Then each result has been compared and discussed to studies conducted in tropical climate countries.

(vi) **Chapter 6: Conclusion and recommendations:** The conclusion and recommendation are explained in chapter six; the research outcome is explained in this chapter. The recommendations for future research related to green technology for bungalows in a tropical climate are suggested at the end of this chapter. Finally, the appendices that might be useful for further studies are provided at the end of the thesis. These include case study layouts, calculation of the U-value of case studies opaque envelope and green envelope, and the result of energy analysis.

1.10 Summary

New building materials are considered vital in regulating indoor air temperature and decreasing the total energy demand of heating and cooling. To effectively preserve a comfortable indoor temperature, the range of material for the building envelope requires careful attention to limit the heat conduction through the building envelope. In this research, one of the natural passive designs will be adapted to cope with solar radiative penetration into the building.

Many researchers have examined the benefits of green vegetation and its correlation to urban plants. They classify the urban vegetation into three categories (public green areas, green walls, and green facades). Only vertical and horizontal systems will adapt to this research; besides, the principal methodology will focus on using a code of energy mitigation for buildings in Malaysia, known as OTTV.

The next chapter presents the literature review and the historical background of the green envelope. It features a review of earlier studies and their recommendations on this technique. In addition to highlighting and explaining the mechanisms in which green envelope aids in alleviating outdoor and indoor air temperatures directly and indirectly. It also highlights the status of energy code globally and locally to control energy consumption, as well the implementation of BIM and VPL on analyzing building thermal performance was briefly summarized.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

International Energy Agency (IEA) stated that energy efficiency enhancement in buildings is one technique for decreasing the world's energy consumption by a third by 2050 and controlling global greenhouse gas emissions. Numerous passive cooling techniques, i.e., louvre shading devices, double glazing, natural ventilation, active vegetation, insulation, and evaporative cooling via a fountain, have been studied by scholars nationwide to boost buildings' energy performance significantly. Each method has several advantages, and numerous scholarly publications have been released on them.

This chapter concludes with a description of the active vegetation (green façade and green roof) to increase buildings' energy efficiency and associated benefits. After that, a comparative study was conducted to determine which systems offer the most benefits compared to others. Among all the strategies, the enhancement of building envelope performance through OTTV, green facades and green roofs were chosen for this study due to their significant benefits for improving building energy efficiency. A comprehensive review of Overall Thermal Transfer Value (OTTV) literature has been conducted in various countries.

Additionally, current processes of energy efficiency improved performance in Malaysia are discussed. The green facade and green roof technologies have been extensively discussed, including plant selection and suitability and thermal and energy performance. Finally, the research gaps associated with enhancing the energy performance of residential buildings in Malaysia subtropical climate were discussed.

2.2 Chapter structure

An extensive amount of literature has been studied during this research and has been discussed in this chapter. The literature review is divided into many sections; each section leads to a subsequent section to maintain content flow. It started with an introduction and chapter framework in sections 2.1 and 2.2. Then section 2.3 described the different green systems found in the literature, and the benefits of using green envelopes are demonstrated in the section well. A mechanism of the heat and mass transfer of the building envelope is shown in section 2.4, studies regarding the mechanism of heat transfer through green envelopes worldwide and locally demonstrated. Section 2.5 outlined extensive literature regarding the Overall Thermal Transfer Value (OTTV) evolution and studied it in different countries generally and in Malaysia, notably.

Moreover, section 2.6 illustrated plants' suitability and thermal and energy performance of green façade and green roof and their relationship to OTTV and Roof Thermal Transfer Value (RTTV) adoption in different countries. Comparative research regarding the implementation of the Building Information Modeling (BIM) and the Visual Programming Language (VPL) applications, a combination for building performance assessment, is demonstrated in section 2.5. The wide-ranging literature reviewed the research gap is presented in section 2.7, followed by summarized the chapter's sections.

The literature review process that covered all the related topics has been demonstrated in Figure 2.1; as illustrated in the graph, the literature review is divided into four parts of the research, i.e., vertical and horizontal green systems, OTTV index, and BIM and VPL. The title, keywords, research problem, objectives, and methodology have been formulated through the extensive studies of this research, as shown in this chapter and the next chapters. The following section outlined the literature on the two categories of green envelopes (vertical and horizontal) and the classification, the benefits of both systems definition, and benefits. On the other side, green façade and green roof' capability to alleviate urban scale air temperature in different types of climates is discussed.

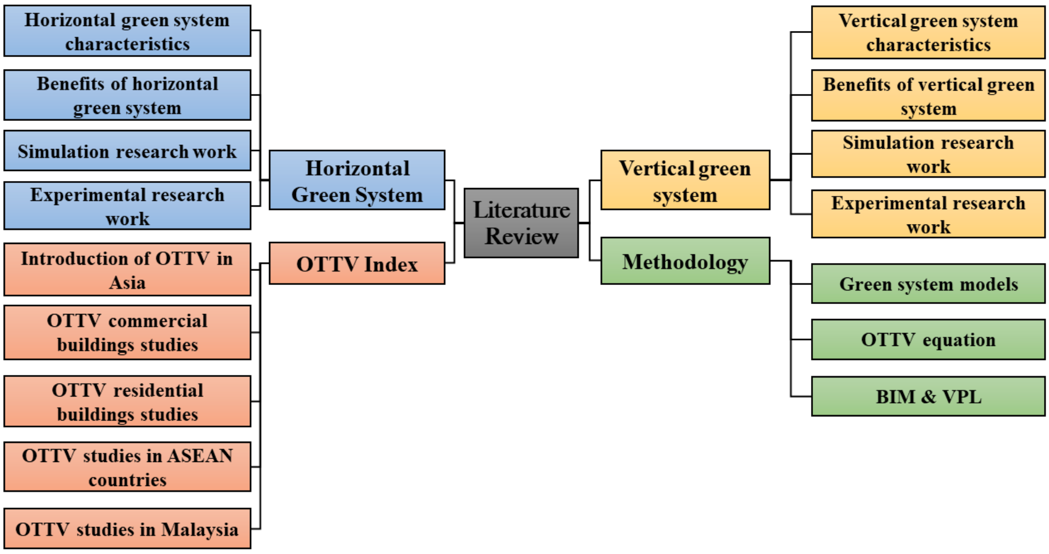


Figure 2.1: Literature review flowchart

2.3 Definition and classification of the green envelopes

The existence of a green envelope dated back to the earliest time of human civilization, the first example of the system appeared 2000 years ago in Mediterranean regions (Kohler, 2008), plants typically used on building façade and roof to shading the building envelope, and cooling the surface during summer (Breuning & Yanders, 2012). The other example of a green envelope showed in the Hanging Gardens of Babylon (Dunnett and Kingsbury, 2008; Wong *et al*., 2010), known as one of the World Seven Wonders, which was built around 600 BC Chaldean King, Nebuchadnezzar as presented in Figure 2.2.

Furthermore, the implementation of the green envelope appeared globally as an example in Central Europe and the UK, the green façade and green roof widespread during the seventeenth and eighteenth centuries (Newton, 2007), while in the 19th century, the system was mainly used as an aesthetical element, especially in North American and Europe (Dunnett & Kingsbury, 2008). In Germany, the implementation of both systems in buildings design created more than 245.500 m^2 of living façade and roof garden in Berlin from 1983 to 1997 (Kohler, 2008).

Figure 2.2: Hanging Gardens of Babylon by Ferdinand Knab, painted in 1886 (Siculus, 2009)

There are currently several types of green façade and green roofs that have been designed and developed all over the world. These systems are broadly classified based on their characteristics, structure, and installation technique as vertical and horizontal green envelopes. The vertical green envelope is considered more widely adopted than the horizontal green envelope because many researchers have witnessed high efficiency. However, the horizontal green envelope is more likely used or more favourable for non-efficient spaces on the top of the buildings, which could be covered with vegetation and significantly change the surrounding environment (Peron *et al*., 2015). Likely, the horizontal green envelope is also more attractive at sites when designed for an aesthetic purpose or recreational like a regular roof garden, but it required close attention during the building's design due to its components' weight.

The vertical green envelope's definition relates to all systems that support vertical surfaces such as walls, partition walls, blind walls, and facades (Newton, 2007). On the contrary, a horizontal green envelope can be in the form of a sloped or a flat surface designed to sustenance vegetation besides working as a fully functioning roof garden (Goddard, Dougill, & Benton, 2010). It is also worth noting that both systems have a distinct difference in the components and the installation technique.

To conclude, numerous studies have noted the awareness of the adoption of both systems since the 1980s to enhance cities ecologically. For instance, a vertical and horizontal green envelope was widespread and manifested the urban planning incorporation at the end of the last century. The following section discusses in more detail these two significant types of green envelopes.

2.3.1 Vertical green envelope

Authors adopted many terminologies when mentioning all sorts of vertical green systems (Cheng, Cheung, & Chu, 2010; Perini *et al*., 2011). Some used the term green façade, vertical garden (Blanc, 2010; Loh & Stav, 2008; Shiah, Kevin; Kim, 2011), green vertical systems (Pérez *et al*., 2011), and bio wall (Francis & Lorimer, 2011).

There are two types of vertical green systems based on the system components, and types of plants used, known as the green facade and living wall (Kevin & Kim, 2011; Loh & Stav, 2008). The use of these systems on building scale or city scale has several advantages not only as an aesthetical value but also as an element that increased the building thermal performance (Lundholm, 2004), as well as a part of passive cooling technique (Sheweka & Magdy, 2011; Zhang *et al*., 2012), and for their environmental, social and economic values (Safikhani *et al*., 2014b).

a. Green façades

A green façade is a vertical system in which hanging shrubs or climbing plants are established using support materials to cover the selected surface, generally in a directed way (Pérez *et al*., 2011). Plants in this system can grow up the vertical wall, like traditional systems, or grow down the surfaces by hanging materials (Dunnett and Kingsbury, 2008). The green façade classifies into two types: direct green façade (Ottelé, 2011), in which the self-clinging climbers can grow vertically without support systems, and the ground act is growing media (Wong & Baldwin, 2016). Moreover, in the direct green facade, a support system is required to help plants grow vertically; thus, in this type, plants can be directly rooted in the planters or the ground. The indirect green façade is classified into two systems:

- **Continuous guides:** This type is constructed on a single support structure such as light wired or metal mesh that guides the plants to grow alongside the entire façade (Pérez *et al*., 2011).

- **Modular guides:** It consists of light trellis modules anchored on independent constructions or the building surface, supporting the plants' growth (Laurenz *et al*., 2005). Figure 2.3 showed the system's structure of direct and indirect green façades.

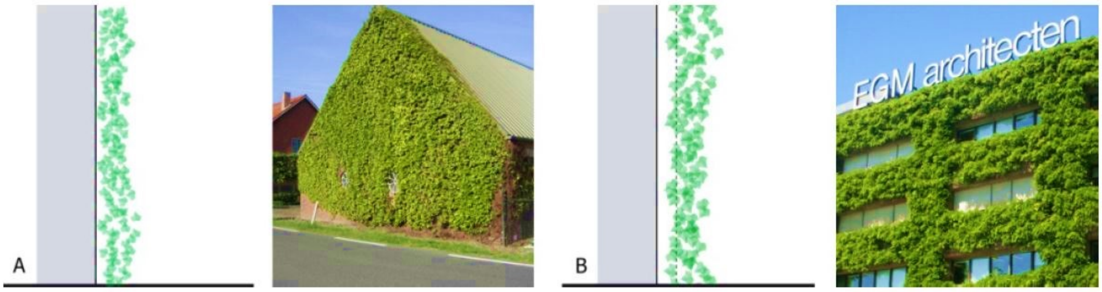


Figure 2.3: (A) Direct green façade attached directly to the building facade; (B) Indirect green façade with a supported system
(Perini & Ottelé, 2012)

ii. Living wall

Living walls are the second type of vertical green envelope that is a moderate invention in wall cladding. It was developed to permit the incorporation of green vegetation in high buildings. Green walls' innovations focused on designing new, flexible systems that include plants, drainage, irrigation, and growing media supporting elements (Fukuzumi, 1996; Tsai, 2012). Living wall categorized into two systems:

- **The continuous living wall** is a constant installation frame covered with flexible and porous layers of root-proof screens attached to the base. This frame is fixed to the wall, creating a void space between the system and the wall to protect humidity. To install selected plants into the system, the external layer of screen cutting form a pocket to hold the plants (Bribach & Rossomano, 2011; Farner, 1977).

- **Modular living wall:** The modular system has differences in structure, composition, and weight. It can be in the form of vessels, trays, flexible bags, or planter tiles as described below:

a. Vessels are the most common support system made from polymeric substances (Manso & Castro-Gomes, 2015).

b. Trays are solid bowls, usually are taking the shape of interlocked parts, made of lightweight materials like metal sheets or plastic (polyethylene) (Lee & Greaves, 2010; Urriola, 2011).

c. Flexible bags contain lightweight materials and a growing media that allow plants' implementation in different forms (Koumoudis, 2011).

d. Planter tiles regularly link to each other by juxtaposition, allowing the plants to insert individually (Fukuzumi, 1996).

Figure 2.4 presents the two living wall systems' continuous and modular designs of a living wall. However, researchers have performed numerous studies to compare the different green wall systems across their system components, cost, maintenance, and type of plan, as illustrated in Table 2.1.

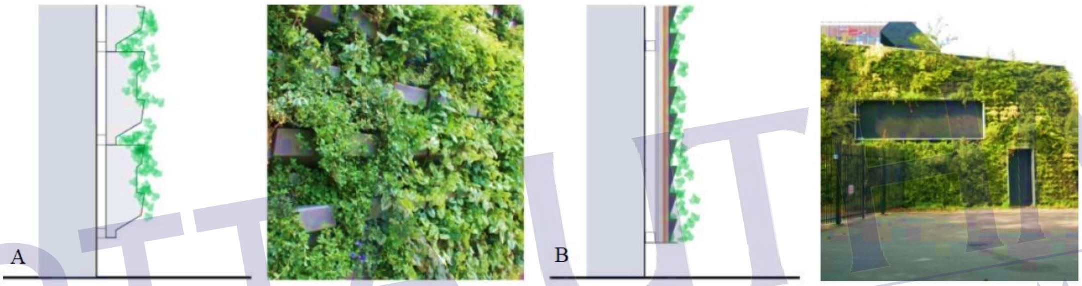


Figure 2.4: (A) Living wall based on planter boxes; (B) Living wall based on felt layers
(Perini & Ottelé, 2012)

Table 2.1: Advantages and disadvantages of vertical green systems
(Ottelé, 2011)

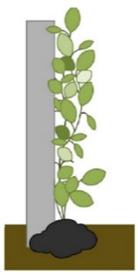
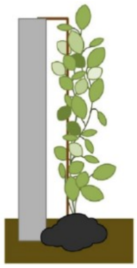
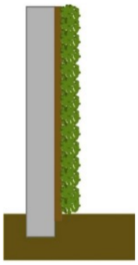
Vertical green system classification	Advantages	Disadvantage
Direct Green façade 	▪ Suitable for retrofit building ▪ Less technical expertise required ▪ No irrigation system required ▪ No materials involved ▪ Low environmental burden ▪ Low planting cost	▪ Limited plant selection ▪ Slow surface coverage ▪ Maintenance costs ▪ Limitation of specific building ▪ Moisture problems ▪ Maximum greening heigh -/+ 25 m

Table 2.1 (continued)

Indirect Green façade 	▪ No direct-attach of vegetation with the envelope ▪ Suitable for retrofit building ▪ Possibility of older green construction ▪ No moisture problem with the façade ▪ No irrigation system required	▪ Limited plant selection ▪ Maintenance cost ▪ Low surface coverage ▪ Maximum greening heigh -/+ 25 m
Living wall 	▪ Plant developed spontaneously ▪ Expensive ▪ The need for an irrigation system ▪ Adaptable to sloped surfaces ▪ Easily disassembled for maintenance ▪ Possibility of various types of plants ▪ Possibility of older green construction	▪ High water and nutrients consumption ▪ Frequent maintenance ▪ Complex implementation ▪ High installation cost ▪ More massive solutions due to growing media

2.3.2 Horizontal green envelope

Several terminologies refer to horizontal green systems such as green roofs, brown roofs, living roofs, and roof gardens (Francis & Lorimer, 2011; Oberndorfer *et al.*, 2007). Jim (2017) stated that the term green roof is "refers to the human-made establishment product on the roof of a house, including erecting a structural framework with appropriate mechanical strength.". According to Breuning and Yanders (2018), to appropriately structured the green roof, the designer must understand how efficiently cooling the roof could be achieved through the green system's different layers. The green roof is mainly divided into an extensive and intensive green roof, later a third type mix between the two systems was introduced.

▪ **Extensive green roof:** is the most familiar type of green roof; commonly, it is applied when no additional structural support is required. The existing roof can support an extensive system weighing 100kg/m^2 (GSA.US, 2011). It consists of several components: a waterproof membrane, a drainage layer, a root protection layer, a growing medium, a filter mat, and, finally, vegetation. Due to the substrate's shallow depth limits the vegetation range to low-growing vegetation types, including grasses, mosses, and sedums. Extensive green roofs need maintenance in the first two years to ensure vegetation is stabilized. Maintenance is relatively minimal to once or twice a year after the first two years.

- **Intensive green roof:** Intensive green roof systems are commonly used to promote food products and provide public facilities. The intensive green roof has similar components as an extensive green roof only the thick of soil substrate and the weight of the system, which usually are 31 cm and over 500kg/m^2, respectively (GSA.US, 2011); however, due to the sensitive relationship between plant types, water harvesting, and rising mediums, each component needs far more attention regarding its shape and materiality. Intensive green roofing needs to match the amount of water harvested, its substrate's fertility, and the variety of vegetation chosen.

- **Semi-intensive green roof:** The semi-extensive green roof combines the two systems, the extensive and intensive one. The semi-extensive green roof requires a slightly deeper substrate depth than the conventional extensive green roof but still enjoys relatively little maintenance of the extensive green roof system. Due to the comparatively deeper substrate, a semi-extensive roof may accommodate a greater variety of vegetation than a broad green roof. The selection of vegetation on the roof in a semi-extensive green roofing system is essential, as it will directly dictate the degree of maintenance needed to keep the green roof working correctly. In general, depending on materials' choice, a semi-extensive green roof can withstand loads of up to 150 kg/m^2 and more (GSA.US, 2011). Table 2.2 illustrates the differences between the three types, whereas Figure 2.5 showed the layer of extensive and intensive green roof systems.

Table 2.2: Summary of the comparison between the green roof systems (GSA.US, 2011)

Comparison	Extensive green roof	Semi-intensive green roof	Intensive green roof
Load bearing component	Concrete - Wood-Timber	Concrete	Concrete - maximum pitch 5%
Soil thickness	7.6 cm – 10 cm	15 cm – 31 cm	Over 31 cm
Drainage layer	No separate drainage layer	Separate drainage layer	Separate drainage system
Vegetation layer	Ornamental and Succulents plants	Ornamental, meadow species, turfgrass, and woody perennial	Ground-level plants
Media type	Course media	Multi-course media	The intensive growth media layer
Irrigation layer	Not required	Required if meadow grass used	Required
Prevalence	Used in an area with sufficient precipitation	Common and provide more plants choice	Less common due to it is structure and maintenance factor
Weight	60 – 150 kg/m^2	25% above or below 150 kg/m^2	200 – 500 kg/m^2
Cost	543 – 690 RM/ m^2	690 RM/ m^2	2259 RM/m^2

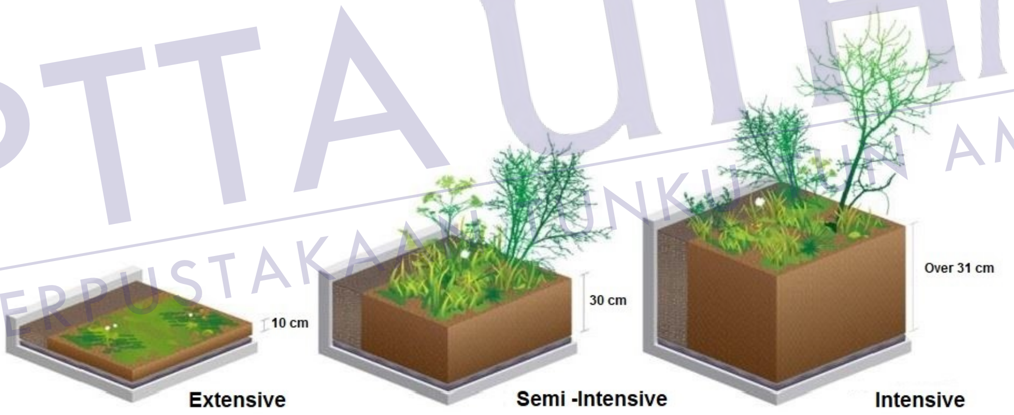


Figure 2.5: Comparison of green roof system based on the soil thickness (Mukherjee, 2013)

2.3.3 Plants selection for the green envelope

Hopkins and Goodwinm (2011) argued that selecting plants suitable for green roofs and living walls is fundamental before being applied due to plants' sustainability under different weather conditions. This sub-section will discuss appropriate plants for vertical and horizontal green systems. The section is critically essential in investigating the green envelope's thermal and energy performance from previous studies, which will later be applied to research case studies.

i. Plants for the vertical green envelope

Plant selection received less attention for the vertical green envelope than for the horizontal green envelope (Hasan, 2013). The suggestion of plants for living wall and green roof systems should be based on plant type, appearance, maximum height, growth rate, soil type, and native or non-native plant habitability for an extended period. Moreover, climate and site-specific considerations, such as aspects, prevailing winds, and shades from other structures, make it difficult to prescribe a set range of plants.

For tropics, Chiang and Tan (2009), over six-month trails in Singapore, suggested a list of plants that can withstand high temperatures and intense sunlight, as well as low soil moisture. Simultaneously, plants that provide thick, dense cover and use crassulacean acid metabolism have been considered preferable. On the other hand, Dunnett, Nagase, and Hallam (2008) recommended using a variety of species and plants that have a clumping rather than an upright growth habit for living wall particularly; however, high species should be avoided as they tend to smother neighbouring plants and overload the support structure.

Hopkins and Goodwin (2011) have set out some criteria for living wall plants; these include a fibrous root system, stem-to-root solid resistance to wind buffering, and good growth habits. Emphasis is placed on the plant's ability to withstand high temperatures and wind speeds and suggested that plants naturally found on cliff tops, or cliff faces are likely to succeed on the Living Wall due to certain similarities between the two environments. According to Conejos (2020), Thunbergia Grandiflora and Bauhinia Kockiana plant, which are native to the tropics, are the most suitable climbers used on the green façade, and in around six months, both types will be able to develop quickly and enter its mature stage. Jain and Janakiram (2016) listed the common plants' species used for living wall and green facade, as mentioned below:

a. Living wall: Dracaena, Phalaenopsis spp, Asparagus sprengeri, Kalanchoe, Cordyline spp. Chlorophytum spp., Haworthia spp., Tradescantia sp, Fittonia spp, Nephrolepsis, Clematis, Gardenia spp., Asplenium nidus, Maranta spp., Cotoneaster, Euonymus fortune, Hedera, Hydrangea, Lonicera, Parthenocissus, Polygonum, Pyracantha, Selaginella, Wisteria, Rose, Petunia, Nasturtiums, Daisies, Bromeliads, and even some vegetables like tomato, chillies, cucumber, peas, lettuce.

b. **Green façade:** Hedera helix, Parthenocissus spp, Hydrangea petiolaris, Polygonum bauldschianicum, Lonicera spp. Clematis spp. Aristolochia spp. Jasminum officinale, Passiflora caerulea. Figure 2.6 presented some of the common plants used for the green façade and living wall.

Othman, Azhar, and Azlan (2018) identify the plant species used for vertical green systems in several commercial buildings in Kuala Lumpur through personal field observation for Malaysia's situation. The observation found that Thunbergia laurifolia, Anemopaegma chamberlaynii, Nephrolepsis biserrate, Philodendron erubescens, Spathoglottis plicata, and Syngonium podophyllum are suitable for living wall and green façade under Malaysia climatic; however, for Thunbergia laurifolia, it found it is encouraging species of insects.

In contrast, a study by Amir *et al.* (2011) mentioned climbing plants such as Pisum sativum, Vigna unguiculata sesquipedalis, Psophocarpus tetrogonobulus, and Phaseolus vulgaris has the best potentials resistance to the Malaysian environment. These peas are durable, efficient at absorbing carbon dioxide, and capable of providing food on a long-term basis. Additionally, we may use the blossoms, leaves, young shoots, and tubers for medicinal purposes in addition to harvesting the fruits for nourishment.

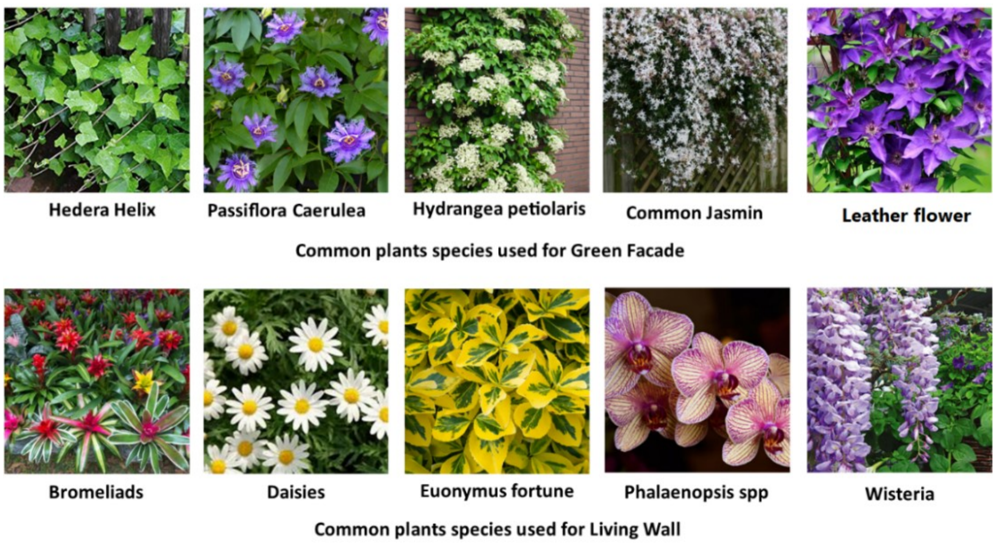


Figure 2.6: Common plants used for green façade and living wall
(Gardenia, 2020)

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