ENERGY AND LIFE CYCLE COST PERFORMANCE OF GREEN WALLS IN SRI LANKA: A COMPARISON OF GREEN VS CONVENTIONAL

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DEDICATION

To my beloved parents and the hidden pillars of my every success….

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The successful completion of this research became reality not solely due to my dedication. Therefore, I make this an opportunity to express my sincere appreciation to all the individuals and organisations, who have supported me during my MSc journey.

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ABSTRACT

Energy and life cycle cost performance of green walls in Sri Lanka: A comparison of Green Vs Conventional

Green walls are becoming an interesting solution to address the potential issues due to the loss of greenery in the urban built environment. Even though green walls offer numerous benefits, the application pace of this concept seems slow in many parts of the world including Sri Lanka, which could be primarily due to the perception that the construction of green walls may involve additional costs compared to conventional walls and due to lack of awareness of its performance. To this end, recent researchers have attempted to investigate the economic performance of alternative types of green walls in different contexts with minimal effort in the comparison of green and conventional walls. Hence, this study aims to assess the LCC of green walls including energy saving potential towards enhancing the adaptation of the green wall concept using a comparative study.

Initially, an extensive literature review was carried out via two main ways; narrative review and systematic review to gain a theoretical understanding of the research area. Subsequently, the data required for the analysis was collected through a preliminary survey, onsite measurements, and documentary review. Two buildings: 1. Conventional building and 2. Buildings with a green wall (indirect green façade) were compared and heat transfer calculations and LCC analysis were performed.

The findings revealed that all three green wall types; direct green facades, indirect green façades, and living walls have been used in Sri Lanka. Amongst, indirect green façade is the most commonly available green wall type. Thermal performance assessment showed that the temperature difference of external and internal wall surfaces of the conventional wall (1.06^0C) is higher than the green wall (0.32^0C). Accordingly, the conventional wall accounts for additional 101 W/m^2 per hour of heat transfer compared to the green wall, and thus green wall can save a minimum of 70% of energy cost for cooling purposes. The analysis further shows that the initial cost of a green wall is 19% higher than the comparable conventional wall. However, maintenance costs of green walls result in 29% savings due to minimum external redecoration time interval. When it comes to the potential energy cost saving for cooling purposes, green walls account for 65% savings compared to a conventional wall. Consequently, green walls offer an overall LCC saving of 55% compared to conventional walls over a period of the reasonably expected lifetime of forty years. Sensitivity analysis further strengthens these findings that for all possible lifetimes and discount rates, green walls show lesser LCC compared to the conventional wall. The findings would facilitate green investors of both public and private sectors to incorporate the application of green walls.

Key Words: *Conventional Wall, Economic Performance, Energy Saving, Green wall, Indirect Green Façade, Life Cycle Cost (LCC), Thermal Performance*

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LIST OF ABBREVIATIONS

Abbreviations		Description
BoQ	:	Bills of Quantities
CBA	:	Cost-Benefit Analysis
CEB	:	Ceylon Electricity Board
HDPE	:	High-Density Polyethylene
IR Thermometer	:	Infrared Thermometer
IRR	:	Internal Rate of Return
LAI	:	Leaf Area Index
LCC	:	Life Cycle Cost
NPV	:	Net Present Value
PBP	:	Pay Back Period
PRISMA	:	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RH	:	Relative Humidity
ROI	:	Return on Investment
UHIE	:	Urban Heat Island Effect

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CHAPTER ONE

INTRODUCTION

CHAPTER ONE

1. INTRODUCTION

1.1 Background

With the increment of population growth and the rapid development of urbanisation, environmental issues have drawn worldwide attention (Fahmy et al., 2020; Chuai et al., 2021). According to the United Nations (2018), the population of cities may rise 60% by 2030 and accounts for 60–80%, 75%, and more than 60% of global energy consumption, carbon emissions, and resource use, respectively. Furthermore, if there are no actions taken regarding the alterations to increase the energy efficiency of buildings, the demand will be increased by 50% for global building energy from 2018 to 2050 (US Energy Information Administration [USEIA], 2019). In addition to the energy crisis, global warming, climatic changes, health problems, loss of biodiversity and rising risk of many natural disasters are some challenges that current society facing, giving rise to the integration of natural vegetation into the built environment (Wang et al., 2015; Olubunmi et al., 2016). To this end, rain gardens, street trees, urban drainage systems, green roofs, and green walls are effective solutions for mitigating and avoiding those issues in urban areas (Shwartz et al., 2014; Manso et al., 2021). Green roofs and green walls are the most preferred solution than others due to the scarcity of land and the numerous benefits in terms of environmental, economic, and social aspects (Zuo et al., 2012; Poddar et al., 2017). Of them, green walls have a greater potential to yield positive outcomes than green roofs because, in multi-storey buildings, the surface wall area is greater than the roof area (Olubunmi et al., 2016; Teotonio et al., 2021).

Green walls are the kind of vertical structures that comprise various plant species (Newton et al., 2007). Mainly, green walls can be split into two groups; green facades and living walls based on the technique used (Dunnet & Kingsbury, 2008). In green facades, plants are directly attached to the wall (Direct green facades) or supported by structures such as steel cables or trellis (Indirect green façade) (Irga et al, 2017; Manso et al., 2021). The living wall systems are designed with a prefabricated or pre-vegetated system on modular panels and did not plant at the ground level (Medl et al., 2017).

Researchers suggest that prevailing environmental issues could be mitigated by incorporating green walls into the built environment. For example, Ottele et al. (2010) and Abdo et al. (2019) identified that the green walls can absorb air pollutants and improve the indoor and outdoor air quality which decreases the respiratory diseases cause due to polluted air. In addition, sound pollution is another burning issue in urban areas due to uncontrollable human activities (Zhang et al., 2014). However, the ability of the noise absorption of green walls would balance the urban noise and make the urban areas more comfortable (Tan et al., 2016). Further, green walls can mitigate the Urban Heat Island Effect (UHIE) which is the main root cause of global warming and climatic changes which are recognised as the most crucial environmental issues. With the rapid movements toward the urban areas, people tend to destroy the plants and as a result, wildlife and their habitats become a threat (Lundholm, 2006). However, green walls can restore habitats and protect the wildlife in urban areas (Medl et al., 2017).

In addition to the environmental perspective, green walls can address the current economic issues too. One of the most common problems is the high electricity charges due to the heating and ventilation requirements (Price, 2010). Green walls help to reduce the energy it takes for ventilation and heating purposes by regulating heat transfer through internal and external environments and thereby reducing the cost of energy (Alexandri & Jones, 2008; Susorova, 2015; Zazzini & Grifa, 2018). Furthermore, green walls enhance buildings' performance by increasing property value (Vox et al., 2018) and building durability (Ottelé et sal., 2011; Lunain & Gauvreau, 2016).

Added to the environmental and economic aspects, green walls promote solutions for the current social issues. Green walls can embrace a quality of life and public health and well-being with the all above environmental and economic benefits (Nowak et al., 2006; Bertram & Rehdanz, 2015). For example, green spaces in cities promote mental as well as physical health by providing psychological relaxation and stress relief (Beatley, 2010; White & Gatersleben, 2011). Further, green walls provide spaces for recreational use and it is more important in urban areas due to the scarcity of land (Rosasco & Perini, 2018). Green walls further enhance the aesthetic appearance of buildings (Beatley, 2010).

Although green walls offer many benefits by addressing the prevailing environmental, economic, and social issues in society, their uptake seems at a slow pace. High initial and maintenance costs, lack of public awareness of the green wall concept, high technology, and breeding of unwanted pests are some factors that hindered the dissemination of this concept. (Naumann et al., 2011). Among these barriers, the high initial and maintenance cost of green walls compared to conventional walls become a major concern. For example, Chew and Conejos (2016) noted that lack of awareness and the high initial cost are major barriers that limit the widespread application of the green wall concept. Similarly, a survey carried out to identify the potential causes for the low green wall adaptation concluded that the majority of the people believe that the green wall implementation will increase the initial cost compared to conventional walls (Wong et al., 2010). Similarly, in the Sri Lankan context, a survey carried out by Jefas et al. (2012) looking into the potential barriers towards the green wall application indicated that the high initial and maintenance cost of green walls relative to the conventional wall is one of the major barriers.

It is therefore essential that the investigation of the cost behaviour of green walls as a matter of significance for clients/investors in the implementation of green walls.

1.2 Problem Statement

The whole world shows a wider growth in urban areas with a huge population and continuous construction with industrial, commercial, and domestic activities. Continuous diffusion of green patches, increase UHIE, making building interiors warmer, releasing air pollutants, increasing urban noise, and adverse climatic effects are some direct results of present urbanisation globally as well as in Sri Lanka (Subasinghe et al., 2016). As a result, most countries including Sri Lanka searching for a sustainable solution to address these problems. The expansion of high-rise building constructions in urban areas provides a sufficient vertical surface to implement green walls which benefit all economic, environmental, and social aspects.

As indicated in the foregoing review cost perspective of green walls determine the spreading of this green wall concept all over the world. Even though when referring to past literature, it is evidenced that there seems to be a limited focus on the cost behaviour of green walls. For example, Perini and Rosasco (2013), compared the costs and benefits of all three green wall types (direct green façade, indirect green façades, and living walls) and pointed out that the direct green façade is the most economical throughout the life cycle than the other two types in Italy. This could be due to the fact that the direct green facade contains only plants while other systems include structural support, irrigation system, waterproof membrane, etc. which contribute to the higher initial, maintenance as well as end life costs.

Similarly, Dong and Huang (2021) examined the Life Cycle Cost (LCC) of a green facade (not specified whether direct or indirect) and four different types of living walls (Blanket, Pocket style, Hanging containers, and Modular containers) in China and revealed that the green façade accounts for less cost compared to all types of living walls considered. Furthermore, the cost of living walls is increased with the material involvement; Hanging containers, modular containers, pocket style, and blankets, respectively. It was further evidenced by Silva et al. (2018) that the initial cost of a living wall considered in the study is fifteen times the initial cost of a green façade (not specified whether direct or indirect) in Portugal. Similarly, Almeida et al. (2020), concluded that the initial cost of a green façade both indoors and outdoors is less compared to the living walls installed both indoors and outdoors.

On a different note, Huang et al. (2019) compared the LCC of different types of green walls: 1. Carrier system (living wall), 2. Planter system (indirect green facade), and 3. Support systems (indirect green facade) are mostly available in Singapore and demonstrated that the indirect green façade with a support system is the most economical while the carrier system is the most expensive option. The support system generally consists of a climber plant that is planted at the ground level with a frame and a mesh, whereas carrier and planter systems need several panels or pots in addition to the frame (structural support). However, in recommending the economical type of green wall, the study has not considered the cost-saving impacts of green walls.

In addition, Perini and Rosasco (2013), Haggag and Hassan (2015), Rosasco and Perini (2018), and Almeida et al. (2020) conducted the Cost Benefit Analysis (CBA) and identified that the economic benefits of green walls; enhancing property value, increasing building/facade durability, rental saving, tax incentives, and energy savings for heating and cooling purposes can balance the cost of green walls throughout the lifecycle. The foregoing review indicates that the previous studies have commonly focused on alternative green wall types and failed to assess the cost behaviour of green walls in relation to a conventional wall which is the most convincing decision criterion for clients/investors in the implementation of green walls. However, the main concern towards the green wall application in both local and international contexts is the public perception that green walls are expensive in terms of initial and maintenance costs compared to conventional walls.

When it comes to Sri Lankan context, the application of green wall concept is still at a primitive stage as evidenced by the research studies. For example, Galagoda et al. (2018) measured the thermal behaviour, Relative Humidity (RH), and CO_2 concentration for the basic three types of green walls and concluded that the living walls are the most suitable green wall type to be implemented in Colombo to optimise thermal benefits. On a similar note, Rupasinghe and Halwathura (2020) revealed that among the available green wall types, living walls show the highest temperature difference in the Colombo area and a better option in terms of thermal performance. Furthermore, Herath et al. (2018) examined the outdoor thermal comfort in Colombo area with the presence of green infrastructure: trees, green walls, and green roofs and concluded that green walls can effectively enhance the urban environment and outdoor thermal comfort with the 1.86^0C temperature reduction. Although these studies have limited their focus to thermal performance assessment, from the perception of the high initial and maintenance cost of green walls compared to the conventional wall seems to be not addressed.

Rajamanna (2019) has adopted a case study approach and evaluated the LCC of direct green facades in comparison to an identical conventional wall. The study concluded that the use of direct green façade contributes to 66% energy saving through an average temperature reduction of 2.5^0C and along with overall 61% LCC saving compared to the conventional wall. However, this LCC saving could be questionable when it comes to an alternative green wall type, because, as per Manso and Castro-Gomes (2015), direct green facades consume less number of components compared to the indirect green façade and living wall types. To this end, Madushika (2020) assessed the LCC of an indirect green façade with a conventional wall in a tropical rainforest climate. The study concluded that green walls result in 45% of LCC saving over a conventional wall. Further, as Perini and Rosasco (2013) suggested even with a particular type of green walls, the life cycle performance may vary based on the plant species used, type of structure, weather pattern, etc. Hence, there is a need for further LCC assessment in different contexts due to the findings of the above study were based on a single comparative case study of a particular location during the period of October to November. Therefore, to address this gap, the current study aims to assess the LCC of green walls in comparison to a conventional wall using an indirect green facade. This would further strengthen the knowledge base as it considers a similar type of green wall to a previous study carried out in the Sri Lankan context with a different support structure and study period.

Accordingly, the research question is set as ‘Are green walls cost-effective compared to conventional walls?’

1.3 Research Aim and Objectives

This research aims to assess the LCC of green walls with reference to energy-saving potential towards enhancing the adaptation of the green wall concept.
To accomplish that aim, the following objectives are formulated.

1. To critically review the green wall application in the global context: types of green walls, and their costs and potential benefits.

2. To identify the green wall applications in Sri Lanka.

3. To assess the thermal performance of a green wall in comparison to an identical conventional wall.

4. To assess the life cycle cost of a green wall in comparison to an identical conventional wall.

1.4 Research Methodology

The study intended to compare the LCC of a green wall with a conventional wall to explore the potential LCC savings of green walls including energy-saving towards enhancing the adaptation of the green wall concept. As set out in the objectives, the current study acknowledged that reality exists independently of beliefs or understanding, where the knowledge depends on objective measurements with the value-free method. Hence, the study was carried out by following a positivist philosophical stance. Furthermore, the abductive research approach was considered as the most suited research approach for the study while quantitative research choice was followed as the most preferred research choice based on the necessity of gaining a deeper insight into the research area.

As the initial step of the study, an extensive literature review was carried out to expand an existing theoretical knowledge of the research area. In doing so, the literature review was conducted in two main ways; narrative review and systematic review. As the first step, the literature review was conducted as a narrative literature review by referring to a number of journal articles, conference proceedings, reports, books, and other publications to gather the existing knowledge on green wall types, technology, benefits, barriers, and green wall application in Sri Lanka. In the second step, a systematic review based upon the publications of the last 13 years utilising three popular databases; Web of Science, Science Direct, and Scopus through the PRISMA technique was conducted to review the economic performance of green walls. Accordingly, Objective 1 was fully and Objective 2 was partially achieved through the literature review.

Data collection was conducted in three stages; preliminary survey, onsite measurements, and documentary review. The preliminary survey was conducted through green rating bodies (mainly GREEN SL and LEED certification), green wall suppliers, site visits, and internet surveys to identify the green wall applications in Sri Lanka (Objective 2) and to examine suitable cases for the case study analysis. As the results of the preliminary survey, an indirect green façade building with a similar-natured conventional building at Galle was considered as a case study profile. Then, to assess the thermal performance of a green wall compared to a conventional wall (Objective 03) external and internal wall surface temperatures of each building were obtained manually using Infrared Thermometer (IR thermometer). A documentary review was carried out to gather the required cost data of each life cycle stage; initial, maintenance, and disposal to assess the LCC of a green wall compared to the conventional wall (Objective 04). Finally, collected data through a preliminary survey was analysed using manual content analysis while collected temperature measurements were analysed using heat transfer calculations, and the collected cost data were analysed using the LCC analysis method. Thereby, conclusions and recommendations were derived from the empirical findings of the study at last.

1.5 Scope and Limitations

Though the literature review discussed three types of green walls; direct green façade, indirect green façade, and living walls in terms of benefits and economic performance, this study focuses only on the indirect green façade type based on the selected case profile and energy cost-saving benefit of green walls for the LCC assessment.

1.6 Chapter Breakdown

The entire study was structured under six main chapters as detailed below.

Chapter 01- Introduction

This chapter presented the introduction to the research with background, problem statement, aim, objectives, methodology, scope and limitations, and outline of the study.

Chapter 02- Research Methodology

This chapter contained the methodological design that has been used to carry out the study, inclusive of the research philosophy, research approach, research choice, research strategy, time horizon, data collection, and data analysis techniques.

Chapter 03- Literature Review

This chapter exhaustively reviewed prevailing literature to get a theoretical understanding of the research area. The initial literature review was conducted as a narrative literature review and thereafter systematic review via the PRISMA technique was conducted by referring to a number of journal articles, conference proceedings, reports, books, and other publications to gather the existing knowledge on green wall application in the global context: types of green walls, and their costs and potential benefits

Chapter 04- Data Collection and Analysis

This chapter included the data collection process conducted through a preliminary survey, onsite measurements, and documentary review. The collected data was analysed using manual content analysis, heat transfer calculations, and LCC analysis.

Chapter 05- Research Findings and Discussions

The key outcomes were outlined and the discussion was conducted on the research findings by revisiting the literature in this chapter.

Chapter 06- Conclusion and the Recommendations

This chapter concludes the research with recommendations, contribution of the study to knowledge and practice, limitations of the research, and further research areas.

CHAPTER TWO

RESEARCH METHODOLOGY

CHAPTER TWO

2. RESEARCH METHODOLOGY

2.1 Introduction

This chapter presents the research methodological design, beginning from the research philosophy, research approach, research choice, research strategy, time horizon, and research techniques adopted in this study to achieve the aim. Most importantly each section in this chapter starts with an overview of each research element and is followed by presenting the adopted research elements for this study with proper justifications. Lastly, a summary is included highlighting the main points described in this chapter.

2.2 Research Process Adopted in this Study

The research process would direct to achieve the research aim through a defined series of stages that illustrates the complete plan of conducting the research. The research design process of the current study is graphically illustrated in Figure 2.1.

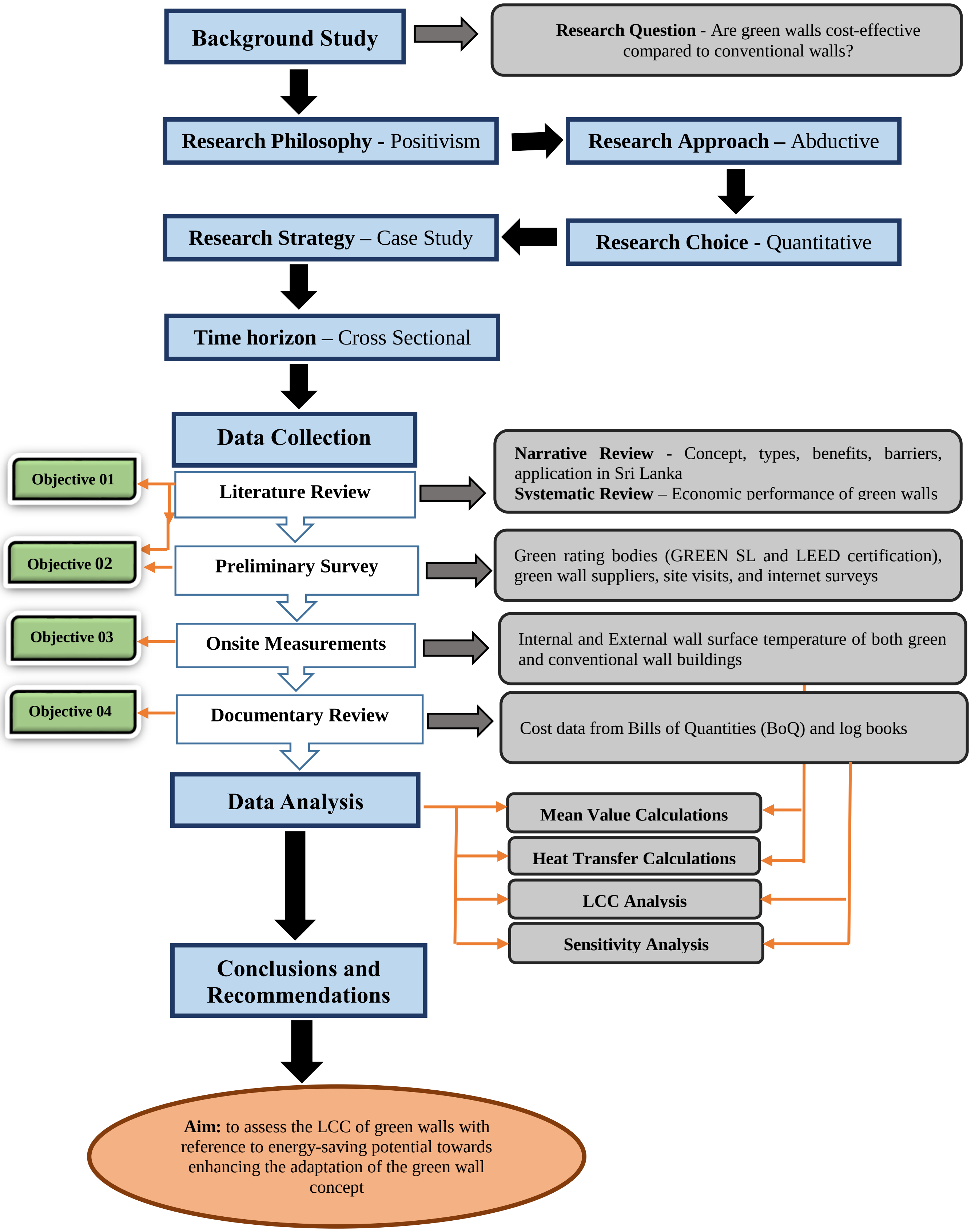


Figure 2.1: Research process adopted in this study

Detailed discussion on each stage of the research process is presented in the subsequent sections.

2.3 Background Study

Initially, a background study was conducted in chapter one to gain a brief understanding of the research area and thereby establish the research gap to be filled in this study. The existing literature regarding green wall concept was reviewed comprehensively based on journal articles, papers from the conference proceedings, e-books, and other publications from the global context to the Sri Lankan context and it was identified that there is a dearth of knowledge on the cost behaviour of green walls compared to conventional walls. Thus, the research aim was to assess the LCC of green walls with reference to energy-saving potential towards enhancing the adaptation of the green wall concept.

2.4 Research Methodological Design

The methodological design of the research is referred to as the detailed procedure of conducting the research (Billing, 2004). Therefore, adopting the most relevant methodology is a significant decision to be taken by the researcher. To this end, researchers developed different types of methodological models that would help to decide the research process for a particular study. The "nested model" by Kagioglou et al. (2000) and the "research onion model" by Saunders et al. (2019) are the two most common research models. The research onion model can be considered as an extension of the nested model, where several new layers were added (Sridarran, 2018). Saunder's research onion model is presented in Figure 2.2.

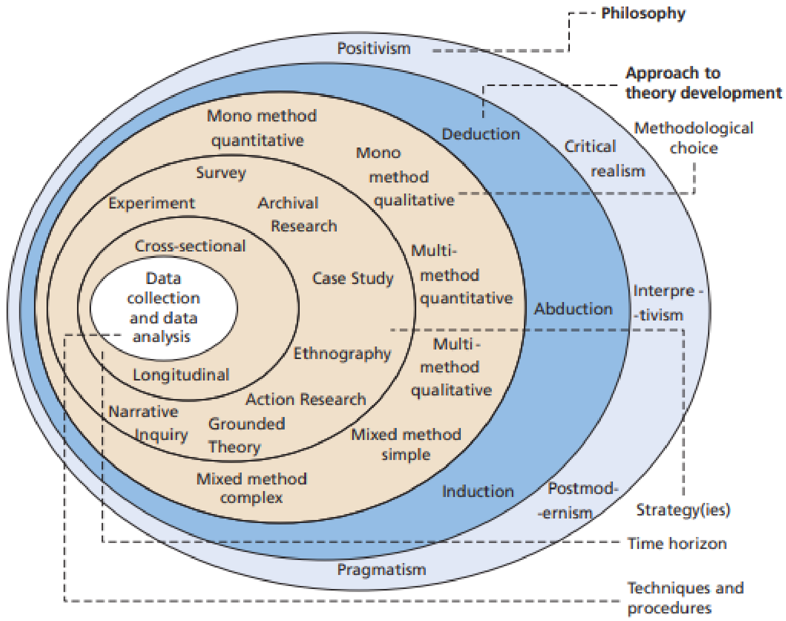


Figure 2.2: Saunder's research onion model

Source: (Saunders et al., 2019)

According to the research onion model of Saunders et al. (2019), there are six layers of research onion; philosophy, approach to theory development, methodological choice, strategies, time horizon, and techniques and procedures. When developing an effective research methodology, the researcher needs to pass these stages sequentially.

Accordingly, the research methodology adopted for the current study is discussed in the next sections based on the layers of the research onion.

2.5 Research Philosophy

Research philosophy is the first layer of the research onion that defines a system of views and assumptions for the improvement of understanding in a certain area of research (Saunders et al., 2019). To understand the philosophical stance of the particular research, there are three major assumptions as ontology, epistemology, and axiology (Žukauskas et al., 2018).

Ontology - Ontology mainly concerns the beliefs about the nature of reality and the social world that exists (Saunders et al., 2019). There are two main extremes of ontology; realism and idealism. As mentioned by Hays and Singh (2012), realism is a belief that the external world has universal truths about reality that can be known, whereas idealism is a belief that there is no pre-determined truth owned by the external world where it should be understood within the contexts in which people live. In this study, the identification of the green wall types applied in Sri Lanka and the assessment of thermal performance and LCC of green walls compared to the conventional wall does not depend upon the ideas or thoughts of different perspectives of people. Since the reality of the study is not based upon human interaction, and reality exists independently of beliefs or understanding, this study is more towards to realistic nature.

Epistemology - Epistemology refers to assumptions about valid, acceptable knowledge and the way of communicating the knowledge to others (Burrell & Morgan, 2019). There are two ends of epistemology as enhancing objectivity and subjectivity. Objectivity deals with observable and evidence-based knowledge that encourages quantifiable observations with statistical analysis. In terms of subjectivity, knowledge is based upon people and their opinions (Saunders et al., 2019). Accordingly, since the current study used the on-site temperature measurements and cost details to assess the thermal performance and LCC of green walls compared to conventional walls, objectivity was highlighted in the epistemological stance.

Axiology - Axiology is concerned with the set of values and ethics that exist throughout the research process, and it questions how researchers are dealing with their own values and ethics as well as with the research participants (Saunders et al., 2019). Basically, axiology assumption deals with the value, and the study may be either value-laden or value-free. In a value-laden study, human values and experiences are considered in the choice of what to do and how to do it in the study while in value-free studies it is based upon the objective criteria (Dudovskiy, 2018). In this study, research results are basically established with an objective basis, therefore it took a value-free stance.

Based on the aforementioned assumptions, three major philosophical stances are introduced as positivism, interpretivism, and pragmatism. Table 2.1 illustrates the relationship of these philosophical stances with the above three assumptions.

Table 2.1: Relationship between philosophical stances and assumptions

Philosophy / Assumptions	Positivism	Interpretivism	Pragmatism
Ontology	Realism	Idealism	Realism and/or idealism
Epistemology	Objective	Subjective	Objective and/ or subjective
Axiology	Value free	Value laden	Value-free and/ or Value-laden

Source: (Aliyu et al., 2017; Dudovskiy, 2018; Grix, 2019; Saunders et al., 2019)

As observed in Table 2.1, basically, positivism focuses on the significance of what is presented in general, with a greater focus on pure data through observable facts and by being independent of the research environment. Conversely, interpretivism is concerned with socially constructed and subjective reality, in which the researcher's interpretations are crucial because they are part of the study. Pragmatism philosophy shows the characteristics of both positivism and interpretivism. Further, Goldkuhl (2012), stated that the pragmatism stance addresses the weakness of both positivism and interpretivism as it is a middle ground between two ends.

Accordingly, it can be summarised that since the current study acknowledged that reality exists independently of beliefs or understanding, where the knowledge depends on objective measurements with the value-free method, positivism is the most appropriate research philosophy for the study.

2.6 Approach to Theory Development

The research approach is the second layer of Saunder's research onion model. The research approach is known as the systematic process of combining research activities together to the aim and objectives of the study. There are three main research approaches to theory development as inductive, deductive, and abductive (Saunders et al., 2019). The inductive approach is also referred to as the "bottom-up" approach where gathering data to identify a phenomenon by allowing a theory to emerge (Soiferman, 2010). Since there is no theory to test in the inductive approach, it is more suitable for the little-known research areas. Conversely, the deductive approach is referred to as "top-down" due to it starts with the hypothesis that is derived from existing literature, and then the empirical investigation is conducted in order to test the accuracy of the particular hypothesis (Park et al., 2020). Figure 2.3 shows the main stages of inductive and deductive reasoning.

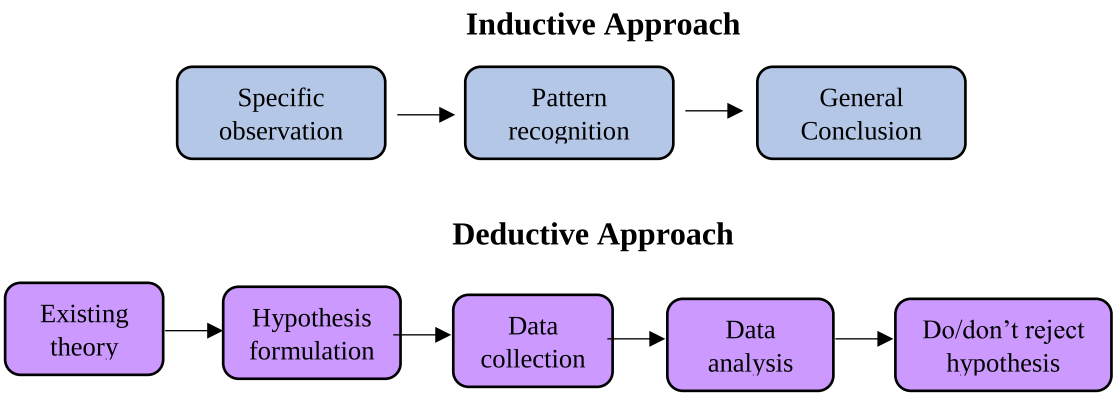


Figure 2.3: Main stages of the inductive and deductive reasoning

Source: (Soiferman, 2010; Saunders et al., 2019; Park et al., 2020)

The abductive approach mainly involves both inductive and deductive approaches where the researcher collects data to investigate a phenomenon in order to develop a novel theory or amend a prevailing theory, which is then verified using extra data collection (Saunders et al., 2019).

Accordingly, the current study initially considered the pre-established theories or knowledge with regards to the green wall concept globally as well as in Sri Lanka and identified knowledge that was further analysed with the collected data to assess the thermal performance and LCC of the green wall compared to the conventional wall and thereby established the further knowledge on green wall concept. Hence, it can be seen that this study has acknowledged the features of the abductive approach and it was identified as the most suited research approach for this study.

2.7 Methodological Choice

The methodological choice is the next layer of Saunder's research onion model. There are three choices for the methodological selection; quantitative, qualitative, and mixed (Saunders et al., 2019). According to Creswell (2013), the quantitative method focuses on numerical data and analyses those data using statistical methods to examine the relationship between the variables. The questions in terms of "how much", "how many", "what", "who", and "where" have been used for the quantitative method (Walliman, 2011). The qualitative method involves collecting data in a textual manner through the views, experiences, beliefs, and attitudes of a specific set of people to become a conclusion (Yin, 2011). Generally, "how" and "why" type questions have been used with the qualitative method (Fellows & Liu, 2015). The mixed method is based on the integration of both quantitative and qualitative data. It can be argued that the mixed method would acknowledge the weaknesses of both quantitative and qualitative methods (Wahyuni, 2012).

The study aims to assess the LCC of green walls with reference to energy-saving potential towards enhancing the adaptation of the green wall concept, "Are green walls cost-effective compared to conventional walls?' begins with the research question of "what" type and placed the research in a quantitative approach. In addition, to assess the thermal performance and LCC of green walls compared to the similar-natured conventional wall, it will be required to guide the research on statistical analysis based on the numerical data collected through records and evidence. Hence, it is evident that the quantitative method is the most suitable research methodological choice.

2.8 Research Strategy

Research strategy is the fourth layer of the research onion model. The research strategy describes the procedure of carrying out the work to accomplish the aim of the study (Yin, 2014). According to Saunders et al. (2019), experiments, surveys, case studies, ethnography, action research, grounded theory, and archival research are the most common and popular research strategies.

Apart from the above-mentioned research strategies, the case study research strategy was used in this study. A case study refers to the in-depth analysis of a bounded system that characterises a particular type of phenomenon (Burt et al., 2017). As a result of the in-depth reviewing nature of the case study strategy, it is mostly applied to the little-known and less literature available research areas. Further, Robson and McCartan (2016) stated that the case study strategy investigates the phenomenon within its real-life context. In general, the case study strategy mostly focuses on contemporary events.

According to Collis and Hussey (2013), a case study can be either a single case or a collection of cases. To this end, multiple case studies increase the accuracy of the research results compared to single case studies (Burt et al., 2017). However, in the situations like unique and critical, single case studies are more appropriate to avoid mistakes and complexity. In addition, a number of cases were chosen for the case studies based on convenience, judgment, cost, and limitations (Yin, 2014).

In this study, it is evident that the case study research strategy can be regarded as the most appropriate research strategy because this study compares the thermal performance and LCC of green walls with conventional walls through an in-depth assessment of real-life applications.

The case study design includes the number of cases, criteria for case selection, and unit of analysis (Yin, 2014). In this study, five criteria were considered in case study selection as; 1) the available types of green walls in Sri Lanka, 2) locality of green wall application within the building, 3) green coverage density, 4) accessibility to the selected location due to the restrictions and prevailing situation of the country, and 5) availability of comparative case – conventional wall. Based on the above criteria, an indirect green façade building and a conventional wall building located in the same location with similar characteristics were considered for the case study analysis. Sub-section 4.2.2 provides further details of the selected case. According to the research question of the study, the temperature measurements of building walls and the cost data of each life cycle stage of buildings are taken as the unit of analysis.

2.9 Time Horizon

Time horizon is the fifth layer of Saunder's research onion model. Time horizon interprets the time frame of the study whether the study targets a particular single point of time or over multiple points of time (Iovino & Tsitsianis, 2020). Accordingly, Saunders et al. (2019) stated that any research can be categorised into two main types as per the study period namely, cross-sectional and longitudinal. Cross-sectional time frame reflects the studies that are focused on a particular single point of time ("Snapshot view") while longitudinal studies collected the data over a long period of time and analysed the change that occurred over that time period (Bryman & Bell, 2011). According to Saunders et al. (2019), case studies (short-term) follow a cross-sectional time frame while case studies (long-term), follow a longitudinal time frame.

In this study, temperature measurements were taken for the twenty-one (21) intermittent days between 23rd May 2022 and 08th July 2022. Accordingly, a short-term case study was applied in this study. Hence, the cross-sectional time frame was adopted in this study. Sub-section 4.3.2.1 provides further justifications for the time frame selection of this study.

2.10 Techniques and Procedures

Techniques and procedures are the last layers of Saunder's research onion model. This layer mainly comprises two stages as data collection and data analysis. Sub-sections 2.10.1 – 2.10.2 discuss the data collection and analysis techniques connected to the current study.

2.10.1 Data collection techniques

The data collection technique refers to the way of gathering required data in order to answer the research question. According to Salkind (2010), mainly, there are two types of data; primary data and secondary data. The data collected from first-hand experience is known as the primary data whereas secondary data refers to the data which are gathered from different existing sources including journal papers, books, online articles, records, etc. (Kabir, 2016). In general, there are different types of data collection techniques are available to collect the data. Mainly, interviews, questionnaires, document reviews, observations, and focus group discussions can be identified as the common data collection techniques (O'Leary, 2004). Accordingly, the current study adopted several data collection techniques at different stages of the study to accomplish the research objectives as depicted in Figure 2.1.

As described in Figure 2.1, objective 01 and objective 02 (partially) were achieved through the literature review. In addition, a preliminary survey was carried out to address the second objective. Finally, on-site temperature measurements and cost data required to fulfil objectives 03 and 04 were collected.

2.10.1.1 Literature review

A literature review is a pragmatic approach that would provide an in-depth understanding of existing knowledge of a particular research area (He et al., 2017). Mainly, there are two types of literature reviews; traditional or narrative and systematic (Bruette & Fitzig, 2014). A traditional or narrative review can cover a wide range of subjects at various comprehensive levels through the existing literature without a specific methodological approach (Rozas & Klein, 2010). However, a systematic review provides a more exhaustive literature review that can be utilised to address the well-structured and specific research problems through a specific methodological approach (Arshed & Danson, 2015).

Accordingly, as the first step, a narrative literature review was conducted to gather the existing theoretical knowledge on green wall concept under different sub-areas including green wall types, technology, benefits, barriers, and green wall application in Sri Lanka. In the second step, the review was further extended using the systematic review technique to critically review the economic performance of green walls. The next subsection represents the methodological approach that was utilised for the systematic review in this research.

Systematic review: Economic performance of green walls

Rather than selecting random literature, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was adopted to improve the quality of the study. According to Benachio et al. (2020), the PRISMA guideline consists of a four-phased flow diagram where it passes through the phases of identification, screening, eligibility, and inclusion and it was used in this study. Search strategy, study selection, and data extraction are very important components in the designing of the PRISMA four-phased flow diagram.

Search strategy

Initially, the research question for the systematic review, "What is the level of the economic performance of green walls in the global context?" was established adhering to the PICO (Population, Intervention, Comparator, and Outcome) search strategy tool (Cooke et al., 2012). Since the research question focuses on economic performance which is more towards quantitative outcomes, the PICO search strategy enables defining a quantitative research question and keywords, the foundation for a systematic search strategy (Schardt et al., 2007, as cited in Cooke et al., 2012). Accordingly, the PICO elements of the research question were identified: Population - Global context, Intervention - Green walls, and Outcome - Economic performance. As the study intends to systematically explore the concept of green walls, it is not necessary to consider an alternative to the identified intervention, i.e., green walls, the comparator element was eliminated from the study (Cooke et al., 2012). Then, a basic logic grid was developed to perform an initial search to identify the relevant key and index terms to include in the comprehensive search strategy. Table 2.2 illustrates the basic logic grid alone with the alternative terms identified for the PICO elements. Here, the term global context was not included in the logic grids as the intention is to retrieve publications covering the whole world.

Table 2.2: Basic logic grid alone with the alternative terms for keywords

Population	**Intervention**	**Outcome**	
Global context	Green wall	Economic	Performance
	Green façade Vertical greenery system Living wall Green garden	Cost Cost?benefit Life?cycle?cost Lifecycle?cost Financial	Capability Feasibility Appraisal Analysis Evaluation Assessment Sustainability
		Sensitivity analys?s	

As observed in Table 2.2, wild cards such as question mark (?) were introduced to several terms to maximize the search results in literature databases. When developing the final search strategy, quotation marks were used to get the exact term and the Boolean operator "AND" was used to combine the PICO elements while "OR" was used to link synonyms identified for each element. The final search string was established as follows after identification and finalisation of all the searched keywords and alternatives.

> ("green wall" OR "green facade" OR "vertical greenery system" OR "living wall" OR "green garden") AND ("economic performance" OR "economic capability" OR "economic feasibility" OR "economic appraisal" OR "economic analysis" OR "economic evaluation" OR "economic assessment" OR "economic sustainability" OR "cost performance" OR "cost capability" OR "cost feasibility" OR "cost appraisal" OR "cost analysis" OR "cost evaluation" OR "cost assessment" OR "cost?benefit performance" OR "cost?benefit capability" OR "cost?benefit feasibility" OR "cost?benefit appraisal" OR "cost?benefit analysis" OR "cost?benefit evaluation" OR "cost?benefit assessment" OR "life?cycle?cost performance" OR "life?cycle?cost capability" OR "life?cycle?cost feasibility" OR "life?cycle?cost appraisal" OR "life?cycle?cost analysis" OR "life?cycle?cost evaluation" OR "life?cycle?cost assessment" OR "lifecycle?cost performance" OR "lifecycle?cost capability" OR "lifecycle?cost feasibility" OR "lifecycle?cost appraisal" OR "lifecycle?cost analysis" OR "lifecycle?cost evaluation" OR "lifecycle?cost assessment" OR "financial performance" OR "financial capability" OR "financial feasibility" OR "financial appraisal" OR "financial analysis" OR "financial evaluation" OR "financial assessment" OR "financial sustainability" OR "sensitivity analys?s")

Study selection

When conducting systematic reviews, it is worthwhile to use multiple databases instead of a single database to obtain more search references. However, searching multiple databases is lengthy and time-consuming, as the composition of search strategies are database specific (Bramer et al., 2017). Given the time and resource constraints and the optimal combination of databases, the current study performed systematic searches in three databases: Web of Science, Scopus, and Science Direct, as those comprised of high-ranking and indexed scientific journals and conferences. Moreover, a manual search was also carried out to extract any other remaining seminal works which satisfied the research question of this study. Once the systematic search into above-mentioned bibliographic databases is completed, the search string was further developed by introducing appropriate filters shown in Table 2.3. Finally, all the records were imported to the Mendeley software for screening and systematic analysis.

Table 2.3: Filters assigned for the literature search

Criteria	Filters	Rationale
Search fields	Title, Abstract, Keywords	To extract all possible and relevant records
Publication year	From 2010 to 2022	Avoiding out-of-date results
Subject/Research area	Environmental science, Engineering, Social science, Material science, Decision Science, Economics, Econometrics, and Finance	Research areas belong to the construction and built environment
Document type	Journal article, Proceedings papers	-
Language	English	English is the worldwide recognised language

Data extraction

The PRISMA flow diagram (Figure 2.4) was used to present the process that was adapted to extract the relevant data from the records retrieved via structured searches performed in bibliographic databases and manually (Liberati et al., 2009).

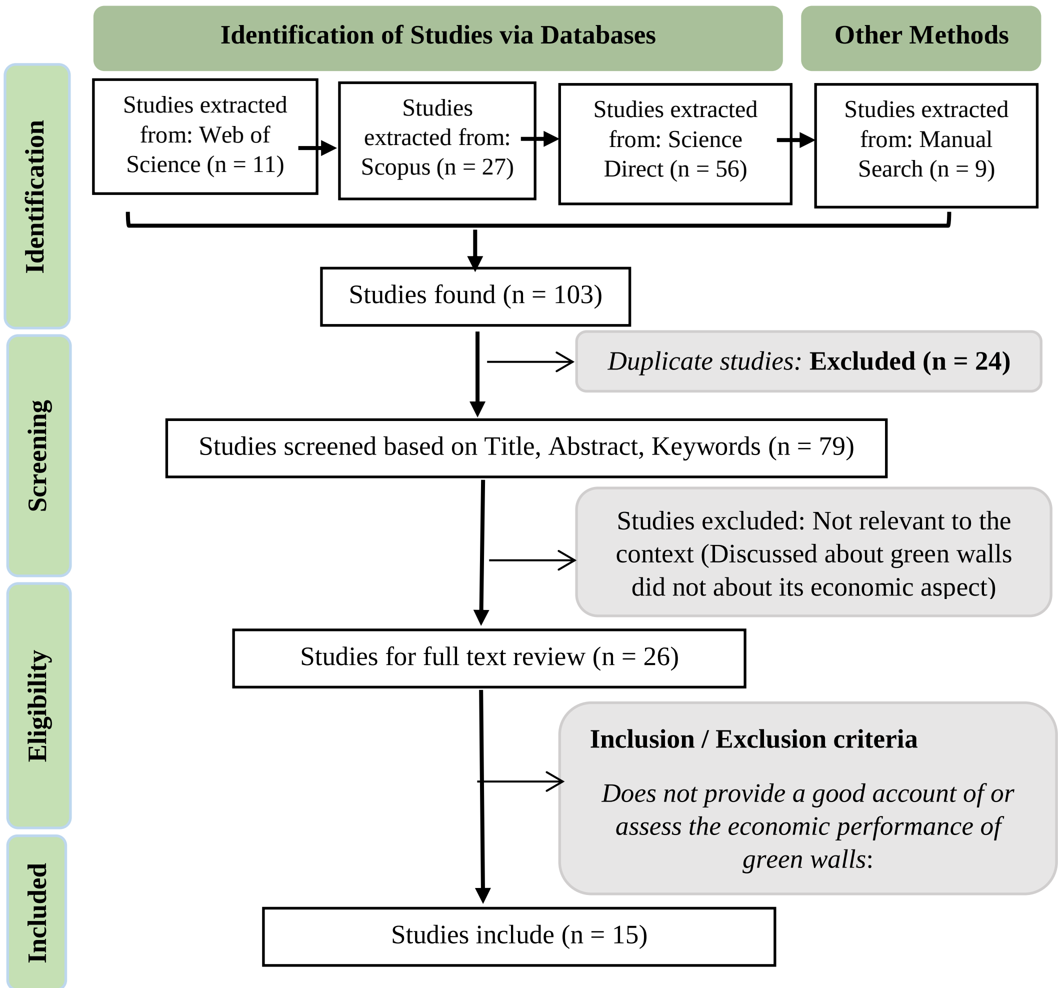


Figure 2.4: Flow diagram of study selection for systematic review

The complete search found 103 studies: 11, 27, 56, and 9 journal and conference articles from the Web of Science, Scopus, Science Direct, and manual search citation, respectively. Amongst, 24 studies were excluded due to duplication. The remaining 79 records were screened using the titles, keywords, and abstracts and 53 of them had no relevance to the research question of this study. Subsequently, the remaining 26 records were sought for full-text; full texts were re-derived for all records, thus all 26 publications were forwarded for an in-depth review. 11 out of 26 publications were excluded as they are not dedicated to the economic performance of green walls. This resulted in 15 journal publications to consider for the review.

2.10.1.2 Preliminary survey

A preliminary survey was carried out with two aims; 1) to identify the green wall applications in Sri Lanka (Objective 2) and 2) to identify a suitable green wall application for the in-depth case study analysis. The green wall applications were sought through possible sources of the green rating bodies (mainly GREEN SL and LEED certification), green wall suppliers, site visits, and internet surveys.

2.10.1.3 On-site measurements

To assess the thermal performance of a green wall compared to a conventional wall (Objective 03), the temperature of external and internal wall surfaces of each building was measured using IR thermometer. In addition, ambient temperature and Relative Humidity (RH) were measured by using the Mini thermometer and RH meter. An illustration of IR thermometer and Mini thermometer and RH meter is shown in Figure 2.5.

(a) (b)

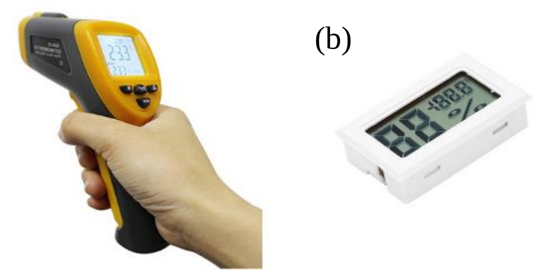


Figure 2.5: IR thermometer (a) and Mini thermometer and RH meter (b)

The laser beam and digital display of the IR thermometer helped to obtain the temperature measurements of exact wall surfaces without reaching the relevant location. As per the specifications of the instrument, accurate measurements can be obtained at 1m away from the relevant object. Further, the temperature measuring range is from -50^{0}C to 380^{0}C and the accuracy is ±2^{0}C.

The mini thermometer and RH meter display both ambient temperature and RH at the same time on its digital screen. It takes approximately 10s of the sampling period to adjust to a certain environment. As per the specifications of the instrument, the temperature measuring range is from 10^{0}C to 50^{0}C and the accuracy is ±1.5°C (at 25°C, 60%RH). RH range is from 10%to 99% and accuracy is 5% RH (at 25°C, 60%RH).

Obtained measurements were noted down in the log sheet and part of the data log sheet (North wall of green wall building) is shown in Table 2.5.

Table 2.4: Sample data log sheet

Time	**Surface Temperature (^{0}C)**						**Ambient Temperature (^{0}C) (0.45m from wall)**		**Relative Humidity (RH) (%) (0.45m from wall)**		**Weather Condition**
	Point A		**Point B**		**Point C**						
	O	**I**	**O**	**I**	**O**	**I**	**O**	**I**	**O**	**I**	
8.00 a.m.											
10.00 a.m.											
12.00 p.m.											
3.00 p.m.											
5.00 p.m.											

Note: O – Outer surface; I – Inner surface

The selection justifications for the points stated in Table 2.5 is detailed in Sub-section 4.3.2.1.

2.10.1.4 Documentary review

To assess the LCC of a green wall compared to the conventional wall (Objective 04) cost data of each life cycle stage; initial, maintenance, and disposal were obtained by referring to the Bills of Quantities (BoQ) and log books regarding the maintenance activities.

2.10.2 Data analysis techniques

The data analysis technique refers to the way of analysing the collected data in order to make conclusions to achieve the research aim. Collected temperature measurements and cost data were analysed as described in the following sections.

2.10.2.1 Analysis of temperature measurements

For temperature measurements, arithmetic and geometric mean values were considered. The arithmetic mean value was calculated in the instances where the temperature measurements were uniform, (i.e., There are no/marginal differences in temperature values of three points considered in each wall orientation at a particular time - Refer Sub-section 4.3.2.2) while the geometric mean value was used in instances where large deviations in temperature were observed (Refer Sub-section 4.3.2.2). Equations 1 and 2 were used to derive the arithmetic and geometric mean, respectively.

Equation 1

$$A = \frac{1}{n} \sum_{i=1}^{n} ai$$

Source: (Holmes et al., 2017)

Note: A - Arithmetic mean; n - Number of values; ai - Data set values

Equation 2

$$\prod_{i=1}^{n} xi^{1/n} = \sqrt[n]{x1x2 \ldots \ldots xn}$$

Source: (Holmes et al., 2017)

Note: Π - Geometric mean; n - Number of values; xi - Values of average

Subsequently, using the calculated mean temperature values, the heat transfer between external and internal wall surfaces of both conventional and green buildings was calculated using Equation 3.

Equation 3

$$\boldsymbol{Q} = \frac{\boldsymbol{K}.\boldsymbol{A}.\boldsymbol{\Delta}\theta}{\boldsymbol{L}}$$

Source: (The Engineering Toolbox, 2022)

Note: Q − Heat Transfer (W); $\boldsymbol{\Delta}\theta$ - Temperature Difference (^{0}C); L -Thickness of Surface (m); K - Thermal Conductivity (W/m^{0}C); A - Heat Transfer Area (m^2)

2.10.2.2 Analysis of cost data

To analyse the cost data, the LCC analysis technique was used in this study. LCC analysis technique focuses on the cost data of each life cycle stage; initial, maintenance, and disposal to ascertain the viability of a certain project in terms of economy (Liu et al., 2016). The outcomes are typically articulated as NPV, which depicts the whole economic effect of the project over its entire lifespan (Cruz et al., 2017). This value can be annualised, which is especially useful when deciding on the most feasible projects that have different lifecycles (Xu et al., 2017). In the LCC calculation of this study, the lifetime of each wall was considered as 40 years.

In the LCC calculation, LCC components that occurred in different time frames were discounted to the base year of 2022 by using Equation 4.

Equation 4

$$PV = \frac{1}{(1+i)^n}$$

Source: (Present Value (PV) Definition, 2022)

Note: PV – Present Value; n - Number of years; i – discount rate

In order to substitute the discount rate for Equation 4, the discount rate was calculated using the discounting formula shown in Equation 5.

Equation 5

$$Discount\ Rate = \left(\frac{1+i}{1+r} - 1\right) \times 100\%$$

Source: (Present Value (PV) Definition, 2022)

Note: i – interest rate; r – inflation rate

The interest rate and the inflation rate were obtained by considering the average lending rate and Colombo Consumer Price Indices for the last thirteen years published by the Central Bank of Sri Lanka. Accordingly, the average inflation, lending, and real discount rates were 5.25%, 10.51%, and 4.99%, respectively (Discount rate calculations are shown in Appendix A).

Finally, the results of the LCC analysis were further validated for sensitivity by considering alternative service life (30, 40, and 50 years) and discount rates (4.76%, 4.99%, and 5.20%). The possible alternative service life of 30, 40, and 50 years was considered based on the literature review findings presented in Sub-section 3.6.3. Similarly, the applicable alternative discount rates (4.76% and 5.20%) were derived by considering the minimum and maximum interest and inflation rates in the last thirteen years.

2.11 Chapter Summary

This chapter outlined the research methodology adopted in this study with a detailed discussion and relevant justifications. Accordingly, under the positivism research philosophy, deductive research approach, and quantitative research choice, a case study research strategy was used in this study in order to gain a thorough knowledge of the economic performance of green walls compared to the conventional wall. Mainly, a preliminary survey, on-site measurements, and documentary reviews were adopted as the data collection techniques where mean value calculations, heat transfer calculations, LCC analysis, and sensitivity analysis were utilised to analyse the collected data.

CHAPTER THREE

LITERATURE REVIEW

CHAPTER THREE

3. LITERATURE REVIEW

3.1 Introduction

This chapter describes the existing knowledge of the key research areas relating to this study through an extensive literature review. The chapter is structured under seven main sections. Initially, gives an understanding of the green wall concept, its different types, and its benefits. The challenges for green wall application follow in the next section. Then, the economic performance of green walls and their energy-saving potential in the global context are discussed. The latter part of this chapter provides current knowledge on green wall applications in Sri Lanka.

3.2 Green Walls

The concept of “green walls” is alternatively referred to “vertical garden”, “vertical greenery system”, “green skins”, “vertical gardening systems”, “vertical greening”, “vertical vegetation”, and “vertical green skin” (Peck et al., 1999; Newton et al., 2007; Manso & Castro-Gomes, 2015; Radiac et al., 2019). It is also referred to vertical structures including facades, walls, blind walls, and partition walls that comprise various plant species (Dunnet & Kingsbury, 2008; Perini et al., 2011; Radiac et al., 2019). Green wall systems mainly comprise a vegetation layer, growing medium, irrigation system, drainage system, waterproofing layer, and structural support (Loh, 2008; Weinmaster, 2009; Perini et al., 2011; Pérez et al., 2011). However, with green wall type, these components may vary. According to the method of construction, there are two main types of green walls; green facades and living walls (Kohler, 2008; Dunnet & Kingsbury, 2008). Figure 3.1 illustrates a detailed classification of green walls.

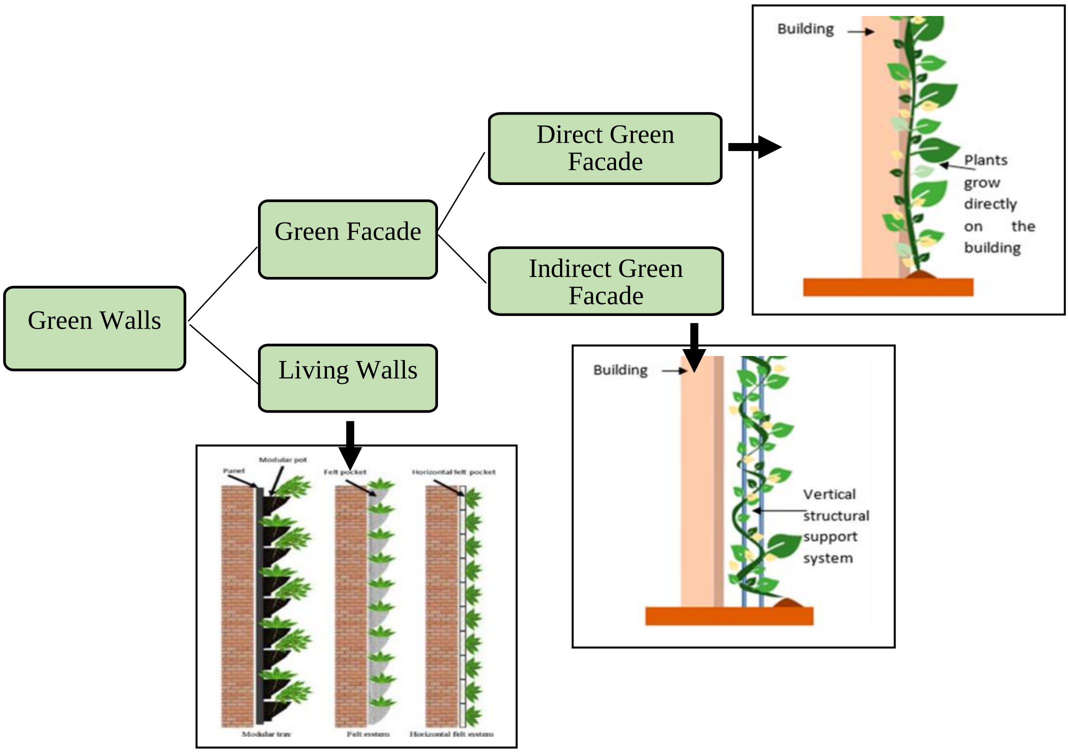


Figure 3.1: Green wall types

Source: (Kohler, 2008; Dunnet & Kingsbury, 2008).

The following sections explain the features of different green wall types.

3.3 Types of Green Walls

3.3.1 Green facades

Green facades are further classified into two, 1) direct green facades and 2) indirect green facades (Kohler, 2008; Dunnet & Kingsbury, 2008; Ottele et al., 2011; Manso & Castro-Gomes, 2015).

3.3.1.1 Direct green facade

In direct green facades, plants are directly attached to the vertical structure and have no support structures (Dunnet & Kingsbury, 2008). Usually, plants are rooted in the ground (Manso & Castro-Gomes, 2015). Therefore, the main component of a direct green façade is the vegetation layer (Kohler, 2008). As a result of that, direct green facades required a minimum initial cost and due to having fewer maintenance activities, their maintenance cost is also very less (Cuce, 2016; Perini & Rosasco, 2016). Furthermore, less material involvement reduces the environmental burden that could be occurred due to the direct green façades (Feng, 2013; Perini, 2018).

Climbing plants are the commonly used plant species for direct green facades and most of the authors have identified that climbing plants are the cheapest solution for green walls (Kohler, 2008). Mainly two types of climbing plants; evergreen and deciduous. Among them, deciduous plants have a strong visual change throughout the year than evergreen plants (Manso & Castro-Gomes, 2015). In terms of direct green facades, both climbing species are used (Beecham et al., 2019).

Apart from the above advantages, there are some disadvantages of direct green facades. Since climbing plants take several years to grow up to a maximum of 25m in height, considerable time needs to be awaited for obtaining the benefits of direct green facades (Dunnet and Kingsbury, 2008; McCullough et al., 2018). In addition, since there were no support structures, there is a risk of falling when the plant grows too heavy and most of the self-clinging destroys the wall surface with their roots (Perini et al., 2013).

3.3.1.2 Indirect green facades

To overcome the above drawbacks of direct green facades, the indirect green façade concept can be used where the vegetation is not directly attached to the vertical structure and separates the plants from the vertical surface using support structures like steel cables, mesh, or trellis (Newton et al., 2007). The primary goal of the support structure is to overcome the disadvantages of direct green facades including vegetation falling and damage to the vertical surface (Yap et al., 2011; Zarandi & Pourmousa, 2018). In indirect green facades, plants can be directly rooted in the ground level or planter boxes (Pérez et al., 2014). Similar to the direct green facades, climbing plants are the most widely used plants for indirect green facades (Kohler, 2008). However, if the plants are rooted in planter boxes, grasses or shrubs could be used (Manso & Castro-Gomes, 2015).

When compared to direct green facades, indirect green facades are expensive in terms of initial and maintenance costs and environmental burdens due to the presence of support structures (Perini & Rosasco, 2013). However, the support structure will help to increase the growing speed of indirect green facades compared to the direct green facades (Manso & Castro-Gomes, 2015). Furthermore, indirect green facades can act as a good thermal buffer due to the air gap present between the vertical surface and the plants (Pérez et al., 2014).

Though the indirect green facades show more performance than the direct green facades, the number of plants that can be used for both direct and indirect green facades is comparatively less and generally, green facades used one type of plant at once (Pérez-Urrestarazu, 2021). Therefore, the plant density and diversity of plants are very less. Further, most of the time, the scattered growth of plants along the surface can be seen (Koch et al., 2020). Therefore, green wall concept moves to the new concept called “living walls” (Manso & Castro-Gomes, 2015).

3.3.2 Living walls

Living walls are prefabricated or pre-vegetated systems on lightweight screens including modular panels, trays, flexible bags, vessels, etc. that contain growing media with balanced nutrients (Andric et al., 2020). Each form of the lightweight screen contains natural or artificial growing mediums with fertilizers, nutrients, and hormones that are required for plant growth (Medl et al., 2017). As a result, living walls show uniform growth with rapid coverage of the vertical surface (Perini et al., 2011). Hence, the living walls take less time to obtain the offered benefits compared to green facades (Riley, 2017).

In addition, living walls used a wider variety of plant species including grasses, shrubs, and herbaceous plants (Beecham et al., 2019). Hence, plant density and the diversity of green walls are higher compared to green façade systems (Pérez-Urrestarazu, 2021). Further, most of the plants used for living walls are evergreen/perennial species (Ghazalli et al., 2018). Therefore, living walls show a more aesthetic appearance than green facades (Fowder et al., 2017).

However, since the living wall systems are more complicated than green façade systems with more material involvement, the cost and the environmental burden of living walls are comparatively high (Manso et al., 2013; Feng & Hewage, 2014)).

Table 3.1 summarises the characteristics of different green wall types.

Table 3.1: Characteristics of different green wall types

Characteristics	Direct green facade	Indirect green facade	Living wall
Vegetation layer	Yes	Yes	Yes
• **Type of plant**	Climbing plants (Evergreen and deciduous)	Climbing plants (Evergreen and deciduous)	Grasses, shrubs, and herbaceous plants (Evergreen)
• **Usable plant species**	Limited	Limited	Wider variety
Support structure	No	Yes	Yes
Growing medium	Yes	Yes	Yes
Irrigation system	Yes / No	Yes / No	Yes / No
	Depends on the plant species used and the climatic condition		
Drainage system	Yes / No	Yes / No	Yes / No
Waterproofing layer	No	Yes / No	Yes / No
Pace of surface coverage	Slow	Average	Rapid
Surface deterioration	Yes	No	No
Maintenance	Low	Average	High
Technology	Low	Average	High
Cost	Less	Average / High	Average / High
		Depends on the amount of material used	
Environmental burden	Low	Average / High	Average / High
		Depends on the amount of material used	

Source: (Kohler, 2008; Dunnet & Kingsbury, 2008; Trusty, 2011; Henry & Frascaria, 2012; Manso & Castro-Gomes, 2015; Muralikrishna & Manickam, 2017)

3.4 Benefits of Green Walls

Green walls provide numerous benefits in terms of economic, environmental, and social aspects (Kohler, 2008; Dunnet & Kingsbury, 2008). These benefits are summarised in Figure 3.2 and detailed in the following sections.

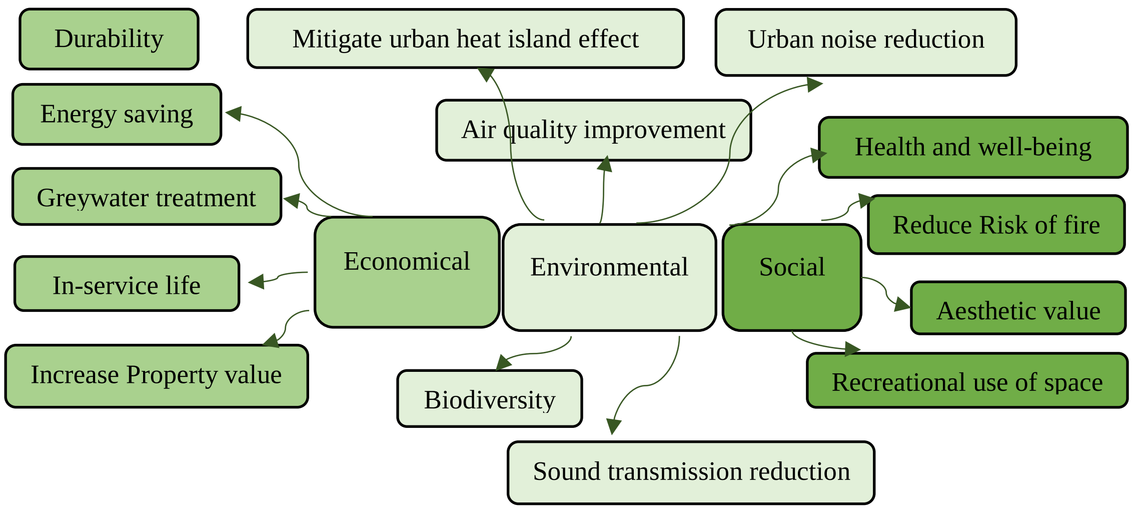


Figure 3.2: Benefits of Green Walls

Source: (Gates, 2003; Kohler, 2008; Dunnet & Kingsbury, 2008; Perini & Rosasco, 2013; Cameron et al., 2014; Kmiec, 2014; Susorova, 2015; Tan et al., 2016; Manso et al., 2021)

3.4.1 Economic benefits

In terms of economic benefits, green walls promote energy saving, increase facade durability, grey water treatment, in-service life, tax incentives, and increase property value as shown in Figure 3.2.

Several studies over the last decade have revealed that green walls have the potential of reducing energy costs by improving building energy efficiency (Susorova, 2015; Olivieri et al., 2017; Libessart & Kenai, 2018). Vegetation presence in green walls has the capability to reduce heat transfer through the internal and external wall surfaces and regulate the building's internal temperature (Gates, 2003). Therefore, green walls reduce the energy requirement for heating, cooling, and ventilation purposes (Larcher, 2003; Straube, 2005).

Since the growing media and plants of green walls act as a biofilter, green walls can be used as the solution for greywater treatment (Masi et al., 2016; Pradhan et al., 2019). Further, in case of that, no significant additional cost is required for green wall irrigation purposes (Svete, 2012; Prodanovic et al., 2017).

In-service life of green walls is another benefit that adds value to the economic condition of the owner. In-service life is determined by the estimated service life of their materials before requiring major repairs or replacement (Ismail, 2013; Manso et al, 2021). According to Perini and Rosasco (2013), green walls have an in-service life of 50 years and it is approximately equal to the building life. However, in-service life is primarily dependent on the materials used for the structure and the construction techniques involved.

Furthermore, green walls influence property value (Veisten et al., 2012). For example, the presence of green walls increases property value by 2% to 5% in Italy (Perini & Rosasco, 2013) while 3.9% in America (Rosiers et al., 2002). Added to that, green walls perform as a protective layer for the external building wall surfaces. Because green wall layer can prevent direct contact of the building's external surface from natural phenomena like solar radiation, rain, snow, etc. (Rosasco, 2018).

3.4.2 Environmental benefits

Green walls have great potential to provide significant environmental benefits when used in urban scale, contributing to UHIE mitigation, urban noise reduction, sound transition reduction, air quality improvement, and biodiversity improvement.

UHIE is the temperature disparity between a specific urban area and its surrounding rural areas (Tan et al., 2016). This phenomenon has a negative impact on public health and comfort (Freed et al., 2008). However, the evaporation process of green walls plant layer counteracts the UHIE. For example, Chen et al. (2013) demonstrated that the living walls can contribute to approximately 1.3^{0}C urban temperature reduction in Cfb climatic conditions while Cameron et al. (2014) showed that the 3^{0}C urban temperature reduction in Cfa climatic conditions from green facades. To this end, green walls can be especially beneficial in cities with warmer climates.

In addition, green walls have the ability of good sound absorption and thereby improve the surrounding acoustic as well as sound transmission into the building interior (Renterghem & Botteldooren, 2009; Renterghem et al, 2013; Manso et al., 2017). For example, the obtained results of Perez et al. (2016) showed a 2dB and 3dB increase with a living wall and green façade, respectively.

Green walls contribute to air quality improvement by removing air pollutants such as NO_2, CO, SO_2, etc. and absorbing CO_2, and releasing the O_2 into the environment (Hui

& Ma, 2017; Fleck et al., 2020). For example, Green walls help to remove 11,7%–40% of NO_2, and 42%–60% of PM_{10}, 40% O_3, 3,5% SO_2, 1,34% CO and also 1,34% $PM_{2.5}$ (Pugh et al., 2012; Jayasooriya et al., 2017).

Improving the natural biodiversity and ecological connectivity is another main benefit of green walls in urban areas (Mayrand & Clergeau, 2018). This is because green walls provide green spaces for a built environment with a wider variety of plants and flowers (Lopucki & Kiersztyn, 2015). Further, it provides habitats for small insects, birds, squirrels, and the like.

3.4.3 Social benefits

Generally, social benefits are difficult to quantify but contribute to a more sustainable urban environment (Sheweka & Magdy, 2011). As shown in Figure 3.2, this is the case for health and well-being, reducing the risk of fire, aesthetic value, and recreational use of space.

Improving urban spaces through the incorporation of green walls act as a tool to promote citizens' health and well-being. For example, green spaces in cities promote mental and physical health by providing psychological relaxation and stress relief (Beatley, 2010; White & Gatersleben, 2011). Furthermore, Hedblom et al. (2019) stated that the psychological effect of green walls can be obtained only by viewing a green space, even if it is inaccessible. People suffering from respiratory diseases such as asthma also can benefit due to the air purification of green walls (Pantavou et al., 2011; Susorova, 2015). In addition, the moisture content of the vegetation layer enables green walls to act as fire resistance (Manso et al., 2021). Furthermore, green walls contribute to the aesthetic appearance of buildings and may be used for recreational purposes (Currie & Bass, 2008; Collins et al., 2017).

3.4.4 Factors affecting the benefits of green walls

As per the review of literature, the benefits of green walls vary with the different factors, and those factors are summarised in Table 3.2.

Table 3.2: Factors affecting the benefits of green walls

Benefits / Factors	Energy saving	Façade durability	Greywater treatment	In service life	Increase property value	Mitigate UHIE	Air quality improvement	Urban noise reduction	Sound transmission reduction	Biodiversity	Health and wellbeing	Reduce the risk of fire	Aesthetic value	Recreational use of space
Plant species used	√	√	√	√	√	√	√	√	√	√	√	√	√	
Foliage thickness	√	√	√	√	√	√	√	√	√	√	√	√	√	
Foliage density	√	√	√	√	√	√	√	√	√	√	√	√	√	
Materials used for the structure	√	√	√	√		√	√	√	√	√	√		√	
Type of modular unit used	√	√	√	√		√	√	√	√	√	√		√	
Green wall type	√	√	√	√		√	√	√	√			√		√
Climate	√	√	√			√	√							
Building type	√				√	√		√	√					
Building location	√				√	√		√	√					
Building orientation	√	√				√	√							
Number of floors of the building	√				√	√								
Composition of substrata layer			√	√										

Source: (Sheweka & Magdy, 2011; Chen et al., 2013; Perini & Rosasco, 2013; Perini & Ottele, 2013; Susorova, 2015; Tan et al., 2016; Perez et al., 2016; Manso et al., 2021)

As observed in Table 3.2, factors like plant species used, foliage thickness, and foliage density almost influence each benefit excluding recreational use of space. Materials used for the structure and type of modular unit used are influencing energy-saving, façade durability, greywater treatment, in-service life, mitigation of UHIE, air quality improvement, urban noise reduction, sound transmission reduction, biodiversity, and health and wellbeing. Further, Table 3.2 evidence that green wall type is the only factor that influences the recreational use of space. Climate condition is mostly influencing energy-saving, façade durability, greywater treatment, mitigating UHIE, and air quality improvement. As per Table 3.2, the number of floors of the building and the composition of the substrata layer influence on least number of benefits.

When considering the energy saving and mitigate UHIE benefits, those are affected by the all identified factors stated in Table 3.2 excluding the factor called "composition of substrata layer". Conversely, benefits like biodiversity, and health and well-being, reducing the risk of fire, aesthetic value, and recreational use of space are affected by four or five factors stated in Table 3.2. To this end, it is clear that the based on above factors can optimise the benefits of green walls.

3.5 Challenges in Green Wall Application

Though green walls provide numerous benefits, their implementation is hampered by a number of factors. Figure 3.3 summarises the challenges associated with the implementation of the green wall concept.

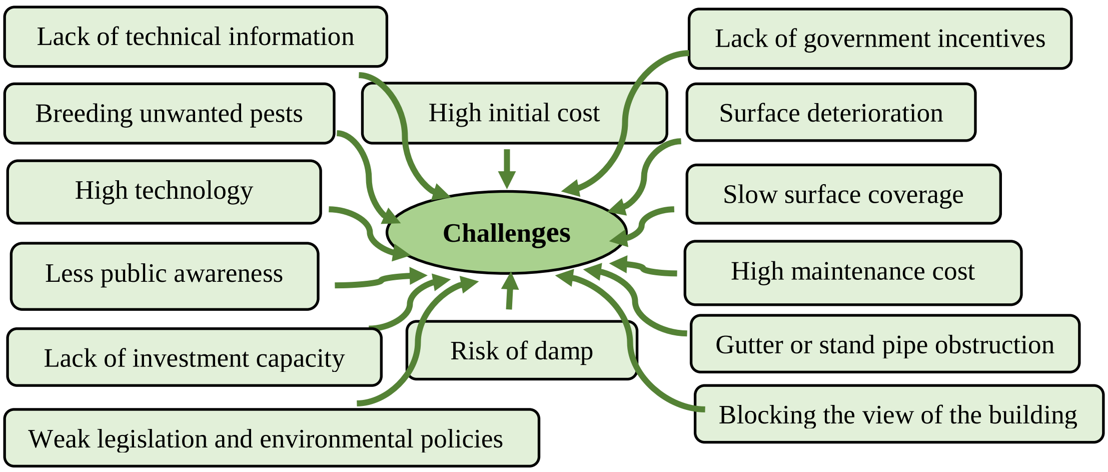


Figure 3.3: Challenges in green wall application

Source: (Dunnet & Kingsbury, 2008; Naumann et al., 2011; Mir, 2011; Behm & Hock, 2012; Chew & Conejos, 2016)

As described in Sub-section 3.3.1.1, surface deterioration, slow surface coverage, risk of dampness, and gutter or standpipe obstructions are mainly seen in the direct green façade systems. However, all these challenges can be mitigated by adopting the indirect green façades or living wall types.

For the long survival of green wall systems, technical knowledge is needed to some extent. For example, if there is no proper pre-arrangement, the plant layer can block the view of green wall applied building (Dunnet & Kingsbury, 2008). As mentioned in Sub-section 3.2, some green wall systems require irrigation systems, drainage systems, waterproofing layers, etc., however, some other systems do not need those components. Hence, before implementing green wall system in a particular location need to consider those kinds of technical aspects. Therefore, at least for the first time implementation of green wall, it is required to seek technical advice. In addition, lack of technical information; suitable plant species, design considerations, and lifespan also affected the spread of green wall application.

According to Grant (2010) and Naumann et al. (2011), lack of public awareness is one of the main reasons that hindered green wall application. Because the degree of green wall implementation mainly depends upon the positive perception of the public on green wall concept, its benefits, and its application. Furthermore, though green walls increase biodiversity due to the presence of birds, insects, and other small animals, there is a negative side to breeding unwanted pests like mosquitoes (Wong et al., 2009).

According to Green Screen (2008) and Behm and Hock (2012), other green concepts like green roofs, and green buildings have legislation towards increasing their applications including offering rewards, and tax incentives. However, it seems to be green walls have no legislation and environmental policies to increase their application.

Green walls required more maintenance compared to other wall systems due to their living nature. Improper maintenance may cause trouble in cost and time (Mir, 2011). In addition, if there is no proper irrigation and green walls become dry, green walls can act as a fire stimulator. The frequent maintenance needs of green walls increase the maintenance cost of green walls compared to conventional walls.

On other hand, Chew and Conejos (2016) pointed out that green wall systems need more capital than conventional walls due to the presence of plant layers and structural support. Similarly, Wong et al. (2010) identified the perception of the high initial cost compared to conventional walls as one of the major concerns of the public regarding green wall propagation through the survey. To this end, a lack of stakeholder involvement and investment capacities can be seen as a result that reduces the client's willingness toward green wall application (Behm &Hock, 2012).

3.6 Economic Performance of Green Walls

As discussed in above sections, the cost behaviour of green walls is one of the major concerns regarding green wall application. Hence it is important to focus on the cost perspective of green walls. When referring to past literature, it is clear that several studies have emphasised the economic behaviour of green walls. The summary of comprehensive studies which elaborate on the economic behaviour of green walls quantitatively is illustrated in Table 3.3.

Table 3.3: Summary of economic performance assessment of green walls

Criteria	Source: Perini and Rosasco (2013)	Source: Haggag and Hassan (2015)	Source: Rosasco and Perini (2018)	Source: Silva et al. (2018)
Climate (Country)	Mediterranean (Italy)	Hot and dry (Abu Dhabi)	Mediterranean (Italy)	Mild Mediterranean climate (Portugal)
Green wall type	Direct green façade (a) Indirect green façade (HDPE) (b) Indirect green façade (Steel) (c) Indirect green façade (HDPE with planter boxes) (d) Indirect green façade (Steel with planter boxes) (e) Living walls (f)	Living walls	Living walls	Green façade (Not specified the direct or indirect) - (a) Living walls – (b)
Method	CBA	CBA	CBA	LCC
Service life	50 years	Not Available	25 and 50 years	50 years
Considered benefits	Increase in property value Heating Air conditioning Façade longevity	Reduction of cooling load Rental saving / Increase property value	Longevity façade Tax reduction Energy-saving for cooling Rent building increase Biomass production	-
Life cycle stages	Initial, Maintenance, Disposal	Initial, Maintenance	Installation, Maintenance, Disposal	Construction, Maintenance, Demolition
Results	see below	**PBP** – 13 – 17 years	**If 25 years** NPV (€/ m²) – 89.24, IRR 8.5% PBP – 10 years **If 50 years** NPV (€/ m²) – 176.08, IRR 9.4% PBP – 10 years	**NPV** a – 1,314,365.24 (EUR) b – 1, 573,957.41 (EUR)

Results – Perini and Rosasco (2013):

	NPV (€)	IRR (%)	PBP (Yrs)
a	21,140	9.40	19.00
b	2,061	5.20	33.00
c	(9,800)	4.30	35.00
d	(18,748)	-	35.00
e	(49,497)	-	>50
f	(92,846)	-	>50

Criteria	Source: Huang et al. (2019)	Source: Almeida et al. (2020)	Source: Dong and Huang (2021)
Climate (Country)	Hot and humid (Singapore)	Mild Mediterranean climate (Portugal)	Sub-tropical Monsoon (China)
Green wall type	Indirect green façade (Planter system) (a) Indirect green façade (Support system) (b) Living walls (Carrier system) (c)	Green façade (Not specified the direct or indirect) - Indoor (a) Living walls – Indoor (b) Green façade (Not specified the direct or indirect) – Outdoor (c) Living walls - Outdoor (d)	Green façade (Not specified the direct or indirect) (a) Living walls (Blanket) (b) Living walls (Pocket style) (c) Living walls (Hanging containers) (d) Living walls (Modular containers) (e)
Method	LCC	CBA	LCC
Service life	30 years	50 years	40 years
Considered benefits	Energy saving	Energy consumption reduction Property value Structure and material longevity	-
Life cycle stages	Initialisation, Installation, Operation & Maintenance, Disposal	Initial (Installation), Maintenance, End life (Replacement)	Design, Construction, Maintenance, Finance
Results	**NPV ($/year)** / **PBP (Yrs)** a: 126.20 / - b: 29.50 / 50% of chance c: 164.00 / -	**B/C ratio** a - 21.64 b - 6.17 c - 13.59 d - 3.01	**Cost ratio from the total cost** **Design** / **Construction** / **Maintenance** a: 3% / 70 – 80% / 10% b: 3-5% / 70% / 20-25% c: 3-5% / 70% / 15-25% d: 3-5% / 50-60% / 15-25% e: 5% / 65-70% / 20%

As shown in Table 3.3, the studies were mainly conducted in the Mediterranean, Mild Mediterranean, Hot and dry, Hot and humid, and Sub-tropical Monsoon. Hence, it is clear that there are less focused on the climate conditions like tropical, temperate, semi-arid, etc. On another note, most studies focus on the economic comparison between alternative green wall types rather than focusing on the comparison with the conventional wall as evidenced in Table 3.3.

In addition, Table 3.3 shows that the CBA and LCC analysis are the two main techniques that have been used to evaluate the costs of green walls. However, the considered the LCC stages, their respective components, service life, and the benefits varied from study to study. Hence, the findings of the above comprehensive studies on the cost behaviour of green walls can be discussed mainly under three sections; 1) LCC stages and components of green walls, 2) The service life of green walls, and 3) The Economic benefits of green walls.

3.6.1 Life cycle cost stages and components of green walls

As discussed in Sub-section 3.2, green walls consist of several components and those components determined the LCC associated with green walls. Accordingly, Table 3.4 illustrates the life cycle stages and the respective cost components referred to in the different studies that focus on the cost behaviour of green walls.

Perini and Rosasco (2013) and Rosasco and Perini (2018) have indicated that the LCC of green walls can be broadly classified into three categories as initial, maintenance, and disposal. Similarly, Huang et al. (2019) also have identified three (03) stages where the initial stage was divided into two subcategories: (1) initialisation (off-site preparation) and (2) installation (on-site preparation) while the other two (02) stages included operation and maintenance and disposal. In the case of operation and maintenance, there was no clear separation of operational cost items and maintenance cost items identified. In another instance, Haggag and Hassan (2015) carried out a CBA where authors considered only two stages which are initial and maintenance while Silva et al. (2018) considered the LCC of green walls in terms of three components: construction, maintenance, and demolition. Almeida et al. (2020) used the term replacement as the last LCC stage. However, the LCC stages considered by

Dong and Huang (2021) are slightly different from the above-mentioned studies. The stages include design, construction, maintenance, and finance.

Table 3.4: LCC stages and components of green walls used in different studies

Sources	LCC Stages	LCC components
Perini and Rosasco, (2013)	Initial	Plants, Pot, panels, support system, irrigation system, installation, transportation
	Maintenance	Pruning, cladding renovation, irrigation, plants replacement, pipe replacement, panels replacement
	Disposal	Green layer disposal
Haggag and Hassan (2015)	Initial	Plants, growing media, installation, irrigation system
	Maintenance	Irrigation
Rosasco and Perini (2018)	Installation	Panels, supporting system, plants, transport, construction
	Maintenance	Pruning, plants replacement, pipe replacement
	Disposal	Disposal
Silva et al. (2018)	Construction	Not specified the cost items further
	Maintenance	
	Demolition	
Huang et al. (2019)	Initialisation	Structure, plants, pot, panel, growing media, irrigation system, drainage system, fertilizers, electricity, water, manpower
	Installation	Transport, installation, electricity, water, manpower
	Operation & Maintenance	Replacement cost of materials, mainly for plants and irrigation systems, fertilizer, electricity, water, manpower
	Disposal	Transport, manpower
Almeida et al. (2020)	Installation	Not specified the cost items further
	Maintenance	
	Replacement	
Dong and Huang (2021)	Design	Design and strategic planning
	Construction	Cost during the construction, including labour and material
	Maintenance	Project operation, maintenance, updates, replacement, and disassembly
	Finance	Project financial support

According to the above review, the three main LCC stages of green walls can be identified as initial, maintenance, and end life, and the cost components belonging to each stage are given in Table 3.5.

Table 3.5: Summary of the LCC stages and components of green walls

Initial			
Initialisation (off-site preparation)	**Installation (on-site)**	**Maintenance**	**End life**
Taking care of plants	Transport to the site	Pruning	Green layer disposal
Support system / Structure	Installation on-site	Cladding renovation	Transport
Plants	Electricity	Irrigation	Replacement
Pots / Panel	Water	Plants replacement	Manpower
Growing media	Manpower	Pipe replacement	
Irrigation system	Design	Panels replacement	
Drainage system		Electricity	
Fertilisers		Water	
Electricity		Manpower	
Water			
Manpower			

Source: (Perini and Rosasco, 2013; Haggag and Hassan, 2015; Rosasco and Perini, 2018; Silva et al., 2018; Huang et al., 2019; Almeida et al., 2020; Dong and Huang, 2021)

3.6.2.1 Initial cost

Initial costs of green walls can be computed through the BoQ or obtained from green wall suppliers. According to Perini and Rosasco (2013) who examined the initial cost of different green wall systems in Italy (Mediterranean climate), the initial cost of green walls varies with the green wall type. The initial cost of the direct green facade is between 30 and 45 €/m^2 and it is the cheapest option in terms of the initial cost. When considering the initial cost of the indirect green façade made of High-Density Polyethylene (HDPE) is about 125 €/m^2 while steel based is about 216 €/m^2. If an indirect green façade is combined with the planter boxes, then the initial cost further increases. However, a living wall can reach a cost of 315 €/m2, the most expensive type, amongst all types. Similarly, Dong and Huang (2021) examined the LCC of a green facade (not specified whether direct or indirect) and four different types of living walls (Blanket, Pocket style, Hanging containers, and Modular containers) in China and revealed that the green façade accounts for less initial cost compared to all types of living walls considered. Furthermore, the initial cost of living walls is increased with the material involvement; Hanging containers, modular containers, pocket style, and blankets, respectively. It was further evidenced by Silva et al. (2018) that the initial cost of a living wall considered in the study is fifteen times the initial cost of a green façade (not specified whether direct or indirect) in Portugal. Similarly, Almeida et al. (2020), concluded that the initial cost of a green façade both indoors and outdoors is less compared to the living walls installed both indoors and outdoors. Conversely, Huang et al. (2019) researched about three types of green walls which are mostly available in Singapore, and showed that the cost involved in the initial stage is 15%, 18%, and 25% of the total cost of a carrier system (Living wall), planter system (indirect green façade with pot), and support system (indirect green façade with frame and mesh), respectively. This could be due to the material involvement of the different green wall systems.

Hence, it can be concluded that the initial cost of green walls mainly depends on the geographical location, type of plant species used, materials used for the structural support, and system (direct, indirect, living wall). In terms of green wall types, a green façade; direct or indirect, is less expensive in terms of initial cost compared to a living wall. However, with the types of materials used in the different green wall systems, especially indirect and living wall types, the initial cost contribution can change. Direct green façade accounts for low initial cost as it consists of less components contributing to the costs of green walls.

3.6.2.2 Maintenance cost

As observed in Table 2.9, pruning, cladding renovation, plants, pipe, and panel renovation are some of the main cost components in the maintenance stage. Generally, climate conditions and plant selection are the two main factors that determine the maintenance conditions (Rosasco, 2018). Some climatic conditions need more irrigation and re-planting than other conditions. However, selecting native plant species can reduce the irrigation needs and other associated costs. In the initial years, green walls need more irrigation and re-planting due to plant adaptation (Huang et al., 2019). In addition, time intervals for each maintenance activity affect the whole maintenance cost. As per the maintenance cost considered by Perini and Rosasco (2013) for different green wall systems in Italy, the maintenance cost of green walls is varied with the system. The maintenance cost of a direct green façade mainly consists of the cost of pruning, hence the cost is less compared to other types. In addition to pruning, the indirect green façade system needs the replacement of materials used for the support structure. However, in the living wall system due to vegetation density and diversity, more material involvement can be seen and thereby responsible for high maintenance costs as well. The above authors further added that in any case, maintenance cost contributes significantly to its LCC, on average 51%–78%. The findings of Almeida et al. (2020) indicated that the maintenance cost of a living wall is twelve times higher than green facade while Silva et al. (2018) stated that it is sixteen times higher. Similarly, Huang et al. (2019) indicated that the operation and maintenance costs together contribute significantly to the LCC of green walls, 84%, 81%, and 74% respectively for the carrier system (Living wall), planter system (indirect green façade with pot), and the support system (indirect green façade with frame and mesh).

The foregoing review concludes that a direct green façade has less maintenance cost than the living wall system due to the types of materials used. However, irrespective of the types of green walls, the maintenance cost consumes the largest part of the LCC of any green wall system.

3.6.2.3 End life cost

End life cost of green walls normally includes the removal of all plants, substrate, support layers, and transportation (Perini and Rosasco, 2013). As per Perini and Rosasco (2013), the disposal cost of green walls also based upon green wall type. For example, direct green façade, indirect green façade (HDPE), indirect green façade (Steel), indirect green façade (HDPE with planter boxes), indirect green façade (Steel with planter boxes), and living wall account for the disposal cost of about 31 € / m^2, 198 € / m^2, 200 € / m^2, 203 € / m^2, 206 € / m^2, and 219 € / m^2, respectively. Similarly, Huang et al. (2019) stated that the living wall system involves high disposal cost compared to the indirect green façade system (Planter and support systems). This higher disposal cost of living walls could be due to the different materials involved in living walls (Radiac et al., 2019). However, in any type of green wall, the end-life cost contribution to the whole life cycle cost is about 1%.

3.6.2.4 Total life cycle cost

As discussed above, having considered the cost at each stage of the life cycle, Perini and Rosasco (2013) noted that the direct green façade is the cheapest green wall type in the Mediterranean climate mainly due to it contains a smaller number of components. The authors further stated that the living wall systems have much higher LCC compared to indirect and direct green façades. Similarly, Huang et al. (2019) identified the living wall system as an expensive green wall type compared to an indirect green façade in a hot and humid climate in Singapore. This is due to the high installation, maintenance, and disposal cost of living walls with its additional cost elements compared to the other two types. It was further evidenced in Portugal (Silva et al., 2018) and China (Dong and Huang, 2021) that the total NPV of the living wall is higher compared to the green façade. When considering the indirect green façade type, the LCC varies with the material involvement. For example, as per the result of Perini and Rosasco (2013) study in Italy, the LCC of an indirect green façade made with steel is higher than the indirect green façade made with HDPE. In case, if the indirect green façade is combined with the planter boxes, the total LCC further increases. Similarly, Huang et al. (2019) considered two indirect green façade systems; (1) the planter system and (2) the support system and found that the planter system results in a higher NPV than the support system in Singapore. Thus, in considering the total LCC, the living wall involves higher costs compared to the other two types and the direct green façade is the cheapest option.

3.6.3 The service life of green walls

As per the gathered data from green wall installation companies, Perini and Rosasco (2013) indicated that the green walls (considered all considered 6 types) would have an in-service life of 50 years. According to the information obtained by Rosasco and Perini (2018) from companies, a service life of 25 years is ideal for green walls. The company further stated that the service life of 50 years can be assumed too, however not guaranteed. Moreover, Huang et al. (2019) assumed that the life span of the green walls is 30 years, because, generally, building renovation is done every 30 - 35 years in Singapore. In addition, Almeida et al. (2020) and Silva et al. (2018), considered 50 years as the service life green wall in CBA, and LCC calculations in Portugal, respectively. Dong and Huang (2021) considered the 40 years of service life for green walls in their study in China. Therefore, as per available literature, the service life of green walls can be assumed to be as 25 – 50 years.

3.6.4 Economic benefits of green walls

As per the review, there are five (05) economic benefits: enhancing property value, increasing building/facade durability, rental saving, tax incentives, and energy savings for heating and cooling purposes. Enhancing property value and energy savings for heating and cooling purposes are the most assessed benefits in CBA studies while other benefits are rarely assessed.

According to Perini and Rosasco (2013), the economic benefits of green walls differ with green wall types. For example, in Italy, the annual energy saving in direct green façades, indirect green façades made of HDPE and indirect green façades made of steel are equal (1,164 €/year) while indirect green façades made of HDPE and planter boxes and indirect green façade made of steel & planter boxes are equal (980 €/year) but the cost of these two types of indirect green facades (later) is less than the direct green façade and former indirect green façades (HDPE and Steel). The living walls contribute to energy saving of 1,870 €/year, the highest saving potential type of green wall. When considering the benefits of façade durability and enhancing property value cost of this study, it is gradually increased with the green wall types of direct, indirect (HDPE and steel), indirect (HDPE + planter boxes and steel + planter boxes), and living wall, respectively. Similarly, Almeida et al. (2020) study results showed that there is a higher property value increment with living walls than with green facades. Although Haggag and Hassan (2015) and Rosasco and Perini (2018) considered the energy-saving benefit, there was no comparison between green wall types. The studies focused only on living walls. However, those two studies also evidenced that the living walls account for energy saving, rental saving, and enhancing property value. Furthermore, According to Rosasco and Perini (2018), tax incentives for green walls play a significant role in the economic assessment of green walls. When tax reduction is introduced, the net results (i.e. NPV) become positive and thereby can increase the number of investors engaged in green wall implementation.

As evidenced the amount of benefit offered by the green wall types differs from context to context. Since there were limited CBA studies, it is difficult to conclude the extent of potential benefits of types of green walls. However, the findings of previous studies considered evidence that the costs of green walls can offset the economic benefits. For example, Haggag and Hassan (2015) showed that the cost of a living wall is 58US$/m^2 while the total cost of benefits offered (reduction of cooling load, rental saving and increase property value) by a living wall is 67.23US$ through CBA. It was further evidenced by Perini and Rosasco (2013) and Rosasco and Perini (2018), with positive NPVs (that is when income prevails over cost).

The most assessed benefits; energy savings of green walls are further discussed in the following section.

3.7 Energy Savings of Green Walls

Several studies over the last decade have presented green wall's ability on building energy saving. Most of the studies considered the reductions in the external and internal surface temperatures of the building wall to establish the energy-saving potential of green walls.

Pérez et al (2014), Larsen et al. (2015), and Reséndiz (2018) identified four mechanisms that help to reduce heat gains and losses through a building façade with the presence of a green layer for energy saving: the shade effect, the cooling effect, the insulation effect, and the wind barrier effect. The findings of some studies regarding the thermal performance of green walls are summarised in Table 3.6, Table 3.7, and Table 3.8, where direct green façade, indirect green façade, and living walls.

Table 3.6: Thermal performance of direct green facades

Source	**Location**	**Climate (Koppen classification)**	**Study Period**	**Façade orientation**	**Plant Species**	**Foliage thickness (cm)**	**Air layer (cm)**	**Sub strata/ thickness (cm)**	**Surface external building wall temperature reduction (^{0}C)**
(Kohler, 2008)	Germany	Cfb	Summer	West	*Parthenocissus tricuspidata*	-	-	-	3
(Eumorfopoulou & Kontoleon, 2009)	Greece	Cfb	Summer	East	*Parthenocissus tricuspidata*	25	-	-	5.7
(Sternberg et al., 2011)	England	Cfb	All year	West-South	*Hereda helix*	10-45	-	-	1.7-9.5
(Perini et al., 2011)	Netherland	Cfb	Autumn	North- West	*Hereda helix*	20	-	-	1.2
(Susorova et al., 2013)	USA	Dfa	Summer	South	*Parthenocissus tricuspidata*	-	-	-	7.9
(Susorova et al., 2014)	USA	Dfa	Jul	North, East, South, West	Climber plants	-	-	-	0.7-12.6
(Cameron et al., 2014)	UK	Cfb	Summer	North, South	*Hereda Helix, Stachys byzantina*	-	-	-	7 – 7.3
(Bolton et al., 2014)	UK	Cfb	Winter	North	*Hereda helix*	-	-	-	0.5
(Haggag et al., 2014**)**	United Arab Emirates	BWh	Summer	-	-	-	-	-	6

Table 3.7: Thermal performance of indirect green facades

Source	Location	Climate (Koppen classification)	Study Period	Façade orientation	Plant Species	Foliage thickness (cm)	Air layer (cm)	Sub strata/ thickness (cm)	Surface external building wall temperature reduction (^{0}C)
(Perini et al., 2011)	Netherland	Cfb	Autumn	North- West	*Hereda helix, Vitis, Clematis, Jasminum, Pyracantha*	10	20	-	2.7
(Pérez et al., 2011)	Spain	Csa	All year	South- East	*Wisteria sinensis*	20	50-70	-	15.18
(Šuklje et al., 2013)	Slovenia	Cfb	Summer	-	*Phaseolus vulgaris*	-	-	-	4
(Cameron et al., 2014)	UK	Cfb	Aug-Sep	South	Climber plants	-	-	-	9.9
(Jim, 2015)	China	Cwa	Summer	East, South, West, North	*Ficus pumila, Campsis grandiflora, Bauhinia corymbosa, Pyrostegia venusta*	-	-	-	Sunny - 5 Cloudy – 1- 2 Rainy – 1 - 2

Table 3.8: Thermal performance of living walls

Source	**Location**	**Climate (Koppen classification)**	**Study Period**	**Façade orientation**	**Plant Species**	**Foliage thickness (cm)**	**Air layer (cm)**	**Sub strata/ thickness (cm)**	**Surface external building wall temperature reduction (^{0}C)**
(Cheng et al., 2010)	Hong Kong	Cwa	Summer	West	*Zoysia japonica*	-	-	-	16
(Jim & He, 2011)	Hong Kong	Cwa	-	South	-	-	15	-	8.83
(Perini et al., 2011**)**	Netherland	Cfb	Autumn	West	Evergreen spieces	10	4	Soil/22	5
(Chen et al., 2013)	China	Cfb	Summer	West	Climber plants	-	3-60	Light substrate/10	20.8
(Mazzali et al., 2013)	Italy	Cfb	Summer	South-West	Climber plants, shrubs and herbaceous	-	3-5	Felt/1	Day: 12-20 Night: 2-3
		Csb	Autumn	South- East		-	5	Soil/5	Day: 12 Night: 3
(Olivieri et al., 2014)	Spain	Csa	Summer	South	Sedum			8 cm substrate and 7 cm extruded polystyrene	15.1 -31.9

From this overview results illustrated in Table 3.6, Table 3.7, and Table 3.8, the thermal behaviour of green walls is clearly influenced by the construction system (method and materials), the climate, the plant species used, foliage thickness, and façade orientation.

For example, according to Kohler (2008), direct green facades with *Parthenocissus tricuspidata* have the potential to reduce the exterior wall surface temperature by 3^{0}C during both winter and summer seasons in Germany. However, Eumorfopoulou and Kontoleon (2009) revealed that a direct green façade with the same plant reduces the 5.7 ^{0}C during the summer season in Greece. Those two studies evidence that the thermal behaviour of green walls could be varied with the climate or region.

In addition, Perini et al. (2011) showed that the direct green façade, indirect green façade, and living walls could reduce surface temperature by 1.2^{0}C, 2.7^{0}C, and 5^{0}C, respectively in Netherland during the Autumn season. It is clear that even in the same region and building orientation, the thermal performance of green walls might be varied with green wall type.

With reference to the thermal behaviour of green walls, previous research has quantified the energy saving of green walls.

For example, according to Perini et al. (2017), green walls with *Parthenocissus tricuspidata* contribute to 34% of maximum energy saving during the summer season in Spain. Further, the simulation study conducted by Afshari (2017) showed that green walls could reduce the energy consumption for air conditioning purposes in Abu Dhabi by 8% while Pan and Chu (2016) found that 16% of energy consumption reduction in Hong Kong.

Wong and Baldwin (2016) predicted that if all the domestic buildings in Hong Kong were retrofitted with green walls, 2651×106 kWh of annual cooling load savings can be gained. Zazzini and Grifa (2018) revealed that the green walls can save a cost of 0.25 €/kWh for electricity as retrofit technology for the Italian school building. Another study conducted in Italy showed that green walls have the potential of reducing 79% of the cooling load during the winter season (Convertino et al., 2019).

According to Coma et al. (2017), indirect green façades and living walls could save 34% and 59%, respectively energy during the cooling season in Spain. In addition, the research results of Cameron et al. (2015) concluded that the green facade implementation will help to increase the building energy efficiency by 40 – 50% in the UK winter season.

3.8 Green Walls Application in Sri Lanka

When considering the studies regarding green wall application in Sri Lanka, only a few studies have been carried out up to date. The summary of identified studies regarding green wall application in Sri Lanka is shown in Table 3.9.

Table 3.9: Summary of green walls-related studies in Sri Lanka

	Content \ Source	**Galagoda et al. (2018)**	**Herath et al. (2018)**	**Peiris et al. (2018)**	**Rahuman and Ranasinghe (2019)**	**Rajamanna (2019)**	**Rupasinghe & Halwathura (2020)**	**Madushika (2020)**	**Perera et al. (2021)**	**Madushika et al. (2021)**
Main Subject area of the study	Thermal Effect	√					√			√
	UHI Effect		√							
	CO_2 Concentration	√								
	Relative Humidity (RH)	√								
	Plant Species						√		√	
	Occupier's Perception	√								
	Influence in Green Rating Systems				√					
	Design of green walls			√						
	LCC					√		√		

Rupasinghe and Halwathura (2020) conducted a photographic survey in Colombo Metropolitan Area and twenty (20) cases were identified and stated that in the current Colombo context, indirect green facades are the most common green wall system, and they are now being used in several novel constructions, particularly in offices, residential, and commercial buildings. In addition, the authors noted that the direct green façade is mostly used for the boundary walls. Moreover, the authors further stated that though many living wall systems are available on a global scale, only planter box-based living wall systems are widely used in Sri Lanka at the moment and the reason is yet be examined.

Galagoda et al. (2018) conducted a questionnaire survey to estimate occupant satisfaction and their perception of green walls in the Colombo Metropolitan Area and identified that 79% of people show a positive perception of green walls. Authors further identified that from the considered sample, 58% were satisfied with the thermal effect, 89.5% and 61% were satisfied with the visual effect and the light penetration level of green walls, respectively. In addition, over 75% of the population tends to own a green wall primarily to improve aesthetic appearance and then for natural clean air maintenance in the surroundings.

Out of the different plants used for green walls, Rupasinghe and Halwathura (2020) and Perera et al. (2021), observed the *Axonopus* Species*; Axonopus compressus,* and *Axonopus fissifolius* show the best thermal performance in a tropical climate. In addition, according to Perera et al. (2021), *Roheo spathacea*, *Elusine indica,* and *Axonopus fissifolius* showed the maximum rate of survival (100%), coverage within 8 weeks of transplanting, and highest Leaf Area Index (LAI) in three (03) different tropical conditions (Colombo, Matara, and Kandy).

As per the review, it is clear that similar to the research results of different countries, Sri Lanka also benefitted from the positive thermal effect of green walls. For example, Galagoda et al. (2018) observed the thermal performance of green walls and showed that the highest temperature difference compared to the conventional wall was 8.0^0C–0.28^0C for living walls, followed by 7.86^0C–1.34^0C indirect green façade, and 6.64^0C–1.34^0C for the direct green facade. As a result, the application of green walls resulted in 10.97MW energy savings with financial benefits. A similar result of maximum temperature reduction of the external wall was 10.16^0C, 8.65^0C, and 6.36^0C, with maximum internal wall temperature reduction as 3.31^0C, 2.32^0C, and 1.99^0C in a living wall, indirect green façade and direct green façade, respectively in Colombo Metropolitan Area has been recorded for Rupasinghe and Halwathura (2020). Hence, the above two studies evidence that the living walls as the most suitable green wall type to be applied in the Sri Lankan context to obtain maximum thermal benefits. On other hand, Madushika et al. (2021) assessed the energy cost saving of green walls compared to the conventional wall and concluded that the indirect green façade with a steel structure showed 1.5^{0}C temperature reduction over the conventional wall which results in 64% energy cost saving in tropical rainforest climate.

In addition, Herath et al. (2018) examined the outdoor thermal comfort in the Colombo Metropolitan Area with six greening design scenarios including prevailing UHIE conditions and identified the temperature reduction of 1.86^{0}C due to the presence of 50% green walls.

Though the living walls show the extreme temperature difference compared to the other two types, in terms of RH, averaged 1.81% RH increment for the indirect green facade system followed by living wall (1.6%) and direct green facade (1.7%) were observed than the conventional wall (Galagoda et al., 2018). The same study revealed that green walls contribute to an average of 0.63% CO_2 concentration reduction than the bare wall in the daytime.

Furthermore, Rahuman and Ranasinghe (2019) conducted a simulation study and identified green facades as a more suitable option than living walls by considering the climate condition only. In addition, Rajamanna (2019) and Madushika (2020) conducted a cost assessment for green walls over conventional wall and a summary of those two studies are presented in Table 3.10.

Table 3.10: Results of Rajamanna (2019) and Madushika (2020)

	Rajamanna (2019)	**Madushika (2020)**
Area	Colombo	Matara
Green wall type	Direct green facade	Indirect green facade
Considered benefits	Energy cost saving for cooling	Energy cost saving for cooling
Service life	50 years	50 years
Method	LCC	LCC
Cost saving results (Negative values are cost saving for green walls)	Initial – (-29%) Maintenance – (-44%) Energy – (-66%) Overall – (-61%)	Initial – (15%) Maintenance – (-25%) Energy – (-64%) Overall – (-45%)

As seen in Table 3.10, a direct green façade contributes to cost saving in all initial, maintenance, and energy perspective while an indirect green façade showed cost saving only in maintenance and energy aspects. In the case of an indirect green façade, the initial cost of green walls is higher compared to the conventional wall due to the presence of a green layer (Madushika, 2020). However, as per Rajamanna (2019), a direct green façade is cost-effective compared to the conventional wall in the initial stage due to the saving of the external surface decoration cost compared to the conventional wall. Further, when compared with the indirect green façade, the direct green façade does not comprise the support structure and it would be another reason for the high initial cost of the indirect green façade compared to the conventional wall.

3.9 Chapter Summary

A comprehensive literature review revealed that a direct green façade is more economical and environmentally friendly compared with indirect green facades and living walls due to fewer components. Followed by indirect green facades and living walls are more expensive and contribute to the environmental burden, respectively. Even though living walls are expensive, it shows the advantage of using many varieties of plants and rapid coverage compared to other types. As a result, living walls provide more benefits in building energy savings, greywater treatment, in-service life, increase building durability, increase property value, improvement of air quality, noise reduction, mitigation of UHIE, biodiversity, sound transmission reduction, health benefits, habitat creation, aesthetic value, and recreational use of space than other types. However, the benefits of green walls did not only depend on green wall type. In the briefing, the climate, building location, materials used for the structure, type of modular unit used, the plant species used, building orientation, foliage thickness, foliage density, and composition of substrata layer are some affected factors to the benefits of green walls. Though green walls offer many benefits, the wide spread of green wall application is hindered by several factors; lack of technical information, breading unwanted pests, high technology, less public awareness, lack of investment capacity, weak legislation and environmental policies, high initial and maintenance costs, etc. Among those barriers high initial and maintenance costs of green walls compared to the conventional wall are identified as major concerns towards green wall application. However, when referring to the available literature it seems that there is less focus on the economic performance of green walls towards the comparison of costs with the conventional wall which is an essential requirement to address the main barrier towards green wall application.

CHAPTER FOUR

DATA COLLECTION AND ANALYSIS

CHAPTER FOUR

4. DATA COLLECTION AND ANALYSIS

4.1 Introduction

This chapter presents the process of data collection and a detailed analysis of the collected data through selected data analysis techniques used to accomplish the aim of the study. The chapter is structured under two main sections; the preliminary survey and the case study analysis. The preliminary survey section discusses the green wall applications in Sri Lanka and the selection of case profile for the case study analysis while the case study analysis section is subdivided into three; case profile, thermal performance assessment of green walls in comparison to conventional walls, and LCC analysis of green walls in comparison to the conventional wall.

4.2 Preliminary Survey

In the initial phase of the study, a preliminary survey was conducted to identify the green wall applications in Sri Lanka (Objective 2) and to find out the most suitable green wall application for the case study analysis. The applications of green walls were reached through possible sources such as, green rating bodies (mainly GREEN SL and LEED certification), green wall suppliers, site visits, and internet surveys as stated in Sub-section 2.10.1.2. Therefore, the sample stated below (Table 4.1) may not represent the entire population of green wall applications in Sri Lanka.

4.2.1 Green wall applications in Sri Lanka

As per the preliminary survey, fifty-seven (57) different green wall applications were found around Sri Lanka. The identified sources include green wall suppliers (19), internet surveys (14), site visits (14), and green certification (10). The details of those green wall applications are summarised in Table 4.1.

Table 4.1: Summary of green wall applications

Building	No	Direct green facade			Indirect green facade			Living wall		
		Ew	**Iw**	**Bw**	**Ew**	**Iw**	**Bw**	**Ew**	**Iw**	**Bw**
Hotel	23	1	1	10	7	-	2	-	1	1
Residential	13	4	-	-	4	-	2	-	3	-
Office	9	-	-	-	7	-	1	1	-	-
Industrial	8	-	-	-	6	-	-	-	1	1
Educational	2	1	-	-	1	-	-	-	-	-
Religious	1	-	-	-	1	-	-	-	-	-
Hospital	1	-	-	-	1	-	-	-	-	-
Total	**57**	**6**	**1**	**10**	**27**	**-**	**5**	**1**	**5**	**2**
		17			**32**			**8**		

Note: Ew – External wall; Iw – Internal wall; Bw – Boundary wall

As observed in Table 4.1, the indirect green façade type is the widely applicable green wall with thirty-two (32) applications. The second most applied type is the direct green façade while the least applied type is the living wall.

The survey findings further revealed that the green walls are placed on the building's exterior or interior walls, or boundary walls. Amongst, the placement on the external wall of the building (34) is higher than the other two placements. In terms of direct green facades, the highest placement is shown in the boundary walls and followed by building external walls. However, considering the application of indirect green facades, it is limited to the external walls and boundary walls where external walls show more application. Living walls are applied in internal, external, as well as boundary walls where internal wall applications are mostly found.

Amongst the type of buildings that incorporate the green walls, hotel buildings show more applications where the direct green façade is the widely used green wall type, and its application is mostly seen in the boundary walls. As per the opinion of the respondents of those buildings, it was clear that this is mainly due to the intention of increasing aesthetic appearance. Next to the hotel buildings, residential buildings show more green wall applications. The other types such as office, industrial, educational, religious, and hospital buildings are now using green walls.

In addition, informal discussions among surveyed building owners and suppliers indicated that in most cases, the intention of having green walls is for aesthetic appearance and to make buildings green from the outer look. Worst still, in many instances, it was not clear the specific type of green wall that was available in the given building. This shows that although the application is somewhat widespread, there is a lack of awareness about the green wall application and its potential in the Sri Lankan context.

4.2.2 Justifications for the selected case study profile

Based on the above analysis, as described previously in Sub-section 2.8, a hotel building with an indirect green façade type and similar-natured conventional wall building at Galle was considered for the detailed case study analysis.

The above-mentioned case was chosen based on five criteria. The first criterion is the availability of green walls in Sri Lanka. It was observed through the preliminary survey and revealed that the indirect green façade is the most widely applied green wall type in Sri Lanka. To this end, out of the 57 identified cases, 32 cases were selected for further consideration (57 – 25 = 32). As the second criterion, consider the locality of green wall application within the building. This is because the green walls placed on the building's exterior walls can give more thermal performance than green walls on interior and boundary walls (Susorova, 2015). Since this case study mainly aims to assess the thermal performance of green walls, it is better to consider the green walls which are placed on the building's exterior walls. Therefore, from 32 cases 5 cases were excluded (32 – 5 = 27). The third criterion discusses the green coverage density on the wall surfaces. As stated in Sub-section 3.4.4, the amount of plant coverage decides the amount of benefits gained from the green walls. Therefore, it is important to select the cases that are having significant plant coverage with foliage thickness to get the maximum benefits. In this context, 16 cases were excluded from the considered cases (27 – 16 = 11). As the fourth criterion, accessibility to the selected cases needs to be considered. This is because of the available time limitation and the prevailing situation of the country. Out of 11 cases, 5 cases were from the western province, 2 cases from the central province, another 2 cases from the southern province, and the remaining case from Sabaragamuwa province. Therefore, by considering accessibility, 2 cases that are from the southern province were selected for further consideration. The presence of similar-natured walls with and without green walls is the final and the fifth criterion that is considered in the chosen suitable case for the case study analysis. This is to increase the accuracy of the research results. Therefore, factors that affect the thermal performance (location, surrounding objects, heating, cooling equipment, etc.) and the LCC analysis (building shape, size, material involvement, the technology used, etc.) were considered while selecting the similar-natured buildings. Figure 4.1 further illustrates the procedure of case selection for case study analysis.

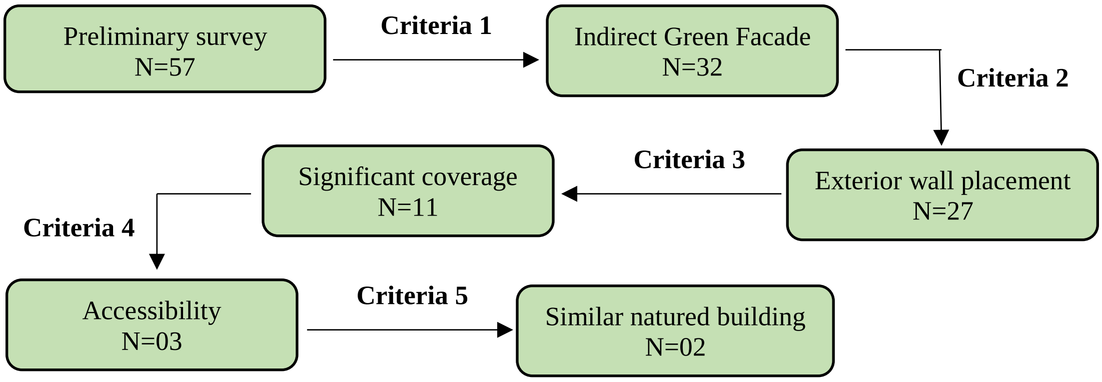


Figure 4.1: Procedure of case selection for the study

Accordingly, two cases were finally considered for the case study analysis. However, of them, one building is a religious building located at Matara and the other one is a hotel building located at the Galle. With the limited time frame, this study was limited to a single comparative case study analysis. Therefore, the hotel building located at Galle was considered for the case study analysis, because the hotel sector used more green wall applications as per the preliminary survey findings.

4.3 Case Study Analysis

In the next phase of the study, a case study analysis was conducted to assess the thermal performance (Objective 04) and LCC (Objective 05) of green walls in comparison to an identical conventional wall.

4.3.1 Case profile

The selected two profiles (building with green walls and without) for this study are three-storey hotel buildings situated on the same land in Koggala, Galle (6.0007° N, 80.3352° E) which is located 24m above sea level. Koggala has a tropical rainforest climate (Af - The Koppen climate classification). General details of selected building profiles are presented in Table 4.2.

Table 4.2: General details of selected building profiles

Description	Green Wall Building	Conventional Wall Building
Location	Galle	Galle
Purpose	Hotel	Hotel
Number of floors	3 floors	3 floors
Floor height	3 m	3 m
Exterior dimensions	Length – 11 m Width – 8 m	Length – 14 m Width – 9 m
Service life to 2022	3 years	5 years
Wall type	Block wall	Block wall
Wall thickness	150 mm	150 mm
Wall Finishing (Internal and External)	Plastering + Painting	Plastering + Painting
Window type	Timber framed glaze windows	Timber framed glaze windows
Door type	Timber Door	Timber Door
Roof type	Flat roof	Flat roof
Electrical Equipment used	Fans, Air conditioners, lights, and heaters	Fans, Air conditioners, lights, and heaters

As shown in Table 4.2, the general details of both building profiles are almost similar. However, in terms of the exterior dimensions of both building profiles, the dimensions of the conventional wall building are higher than the building with the green wall. Conventional wall buildings being are in operation since 2015 whereas green wall buildings being are in operation since 2017. Further, the longitudinal sides of both buildings are oriented in the North and South directions. Without obstruction from surrounding objects, all sides of both buildings are completely open to the sunlight. Since both buildings have similar functions, fans, air conditioners, lights, and heaters are the frequently used electrical equipment.

Green wall building comprises the indirect green façade type. The plant is planted on the ground and grown with the support of the timber frame. Cinnamon and Kubuk were used for the timber support structure. The average distance between the climbing plant and the exterior wall is 1m. The climbing plant is well grown and covered all four wall surfaces of each three floors. The average foliage thickness of the indirect green façade is 40 cm. *Thunbergia laurifolia* is the climbing plant used in this building. This plant is commonly known as the "Laurel clock vine", "Blue Trumpet vine", or "Blue sky vine" (Starr et al., 2003). This plant is a perennial and most suited for the tropical climate. As a result of that, there is no need for an irrigation system for this green wall. Further, a waterproofing layer and drainage systems were also not applied to this green wall.

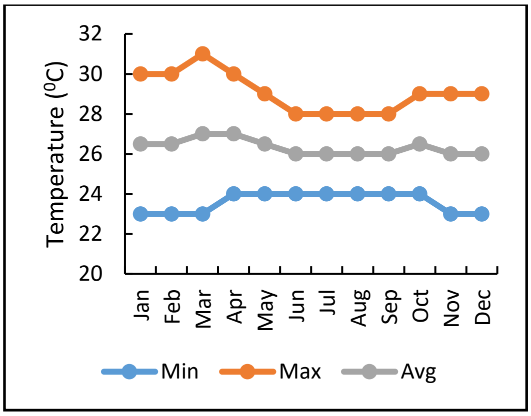
4.3.2 Thermal performance assessment: Green vs. Conventional walls

To assess the thermal performance of green walls in comparison to conventional walls heat transfer through the external wall surfaces was obtained. As the initial step, temperature differences of external and internal wall surfaces were obtained by measuring the surface temperature of both external and internal wall surfaces of each floor of both buildings with RH and ambient temperature. The detailed process of measuring temperature is presented in the subsequent sections.

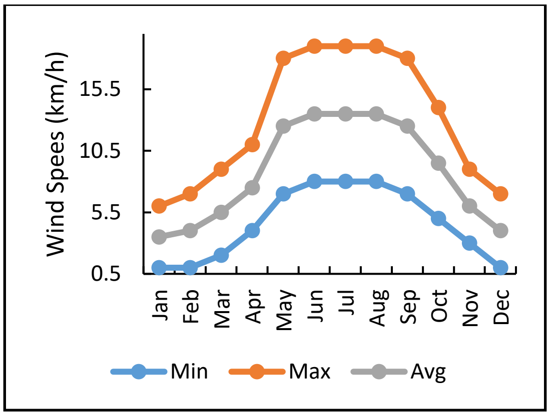
4.3.2.1 Temperature measuring process

Study period selection

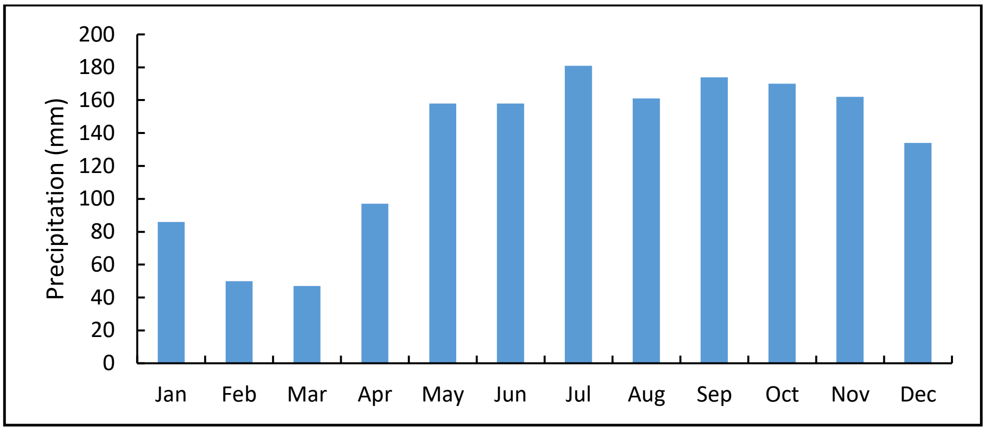
Prior to taking the temperature measurements, an appropriate study period was selected by considering the boundary conditions of the two building profiles. Accordingly, the temperature, wind speed, and precipitation of this area were observed. Figure 4.2 illustrates the above boundary conditions behaviour of the selected case profile location over the last 30 years.



(a)



(b)



(c)

Figure 4.2: Temperature (a), speed (b), precipitation (c) behavior of the Koggala, Galle over the last 30 years.

Source: (Meteoblue weather, 2022)

As per Figure 4.2, March and April are the warmest months of the year has a maximum of 31^0C and an average of 27^0C temperature. The months of June, July, and August shows the highest average wind speed of 13.5 km/h. Further, May to December shows high precipitation of above 150 mm that account for the wet season.

Considering the time permitted for the study, it was difficult to obtain the temperature measurement over 12 months. Since the ultimate target of obtaining temperature measurement is the assessment of the thermal behaviour of the green wall and thereby promoting the green wall concept, temperature measurements were taken over the months that show minimum temperature behaviour. Then the results can be obviously applied to the months that show maximum temperature behaviour. To this end, temperature readings were taken for twenty-one (21) days intermittently over the period end of May to the beginning of July (23rd May to 08th July). Since the intensity of solar radiation received throughout the day is not constant, temperature readings were taken at five-time intervals per day that started from 8.00 A.M to 5.00 P.M.

Point selection

Solar radiations are also not uniformly distributed across the wall surface and can vary depending on the wall orientation, surface composition, and surrounding objects. However, according to the surrounding nature of the selected building profiles, there were no objects that make any obstructions to the wall surfaces of each building. Further, the composition of the wall surfaces is also similar in each building. Therefore, to avoid any error that can be occurred due to the wall orientation, temperature readings were obtained from a few points on external and internal wall surfaces of each floor of both buildings. Figure 4.3 presents the sample of point selection for the first floor of the green wall building.

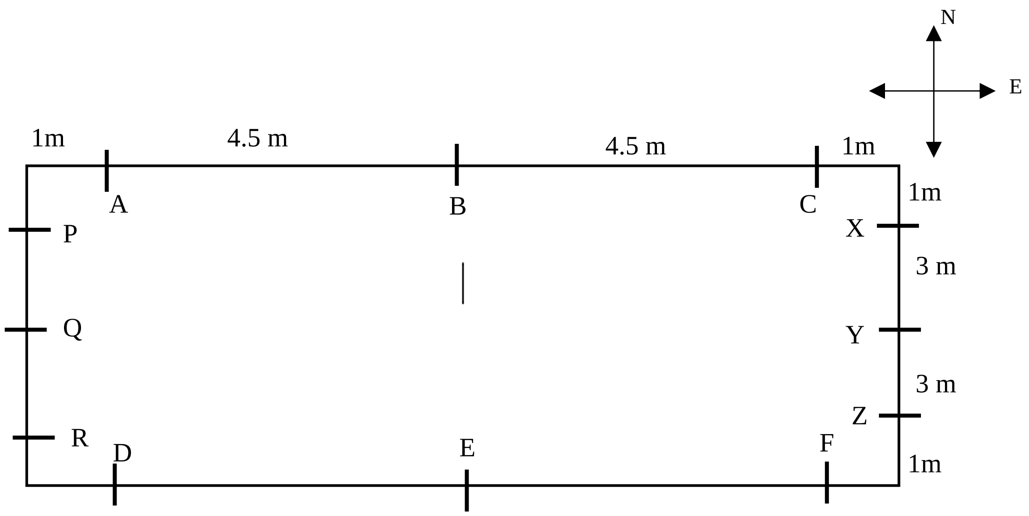


Figure 4.3: Sample of point selection for the first floor of the green wall building

As observed in Figure 4.3, 1m from the corner of each wall was excluded to avoid any error that could be occurred due to the temperature influence of adjacent walls. Then three points with equal spacing were selected as shown in Figure 4.3. Similarly, point selection for other floors as well as the conventional building was also conducted.

When measuring RH and the ambient temperature, the RH meter was kept 1m above the floor level of each floor and 500m parallel away from the wall to avoid the error that could be occurred due to the heat emissions of the floor and wall surface, respectively.

4.3.2.2 Thermal behaviour of green wall and conventional wall

As per the collected data, it seems to be the behaviour of the temperature measurements is successive throughout the study period. Hence, common justifications have been made based on a sample of the temperature data 12th day (7th July 2022) of the green wall and conventional wall (Refer Figure 4.4 – Figure 4.15).

The average temperature of the green wall - 7th July 2022

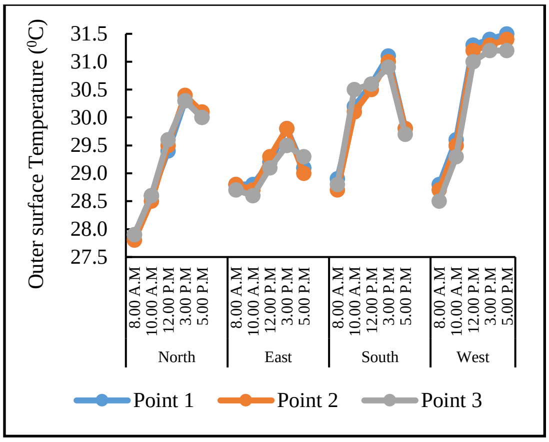


Figure 4.4: Green wall – Ground floor (O)

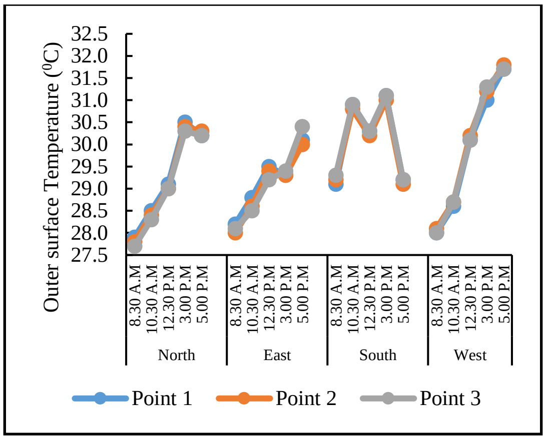


Figure 4.5: Green wall – First floor (O)

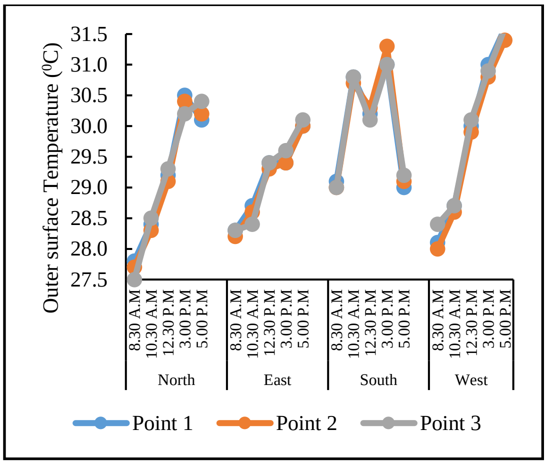


Figure 4.6: Green wall – Second floor (O)

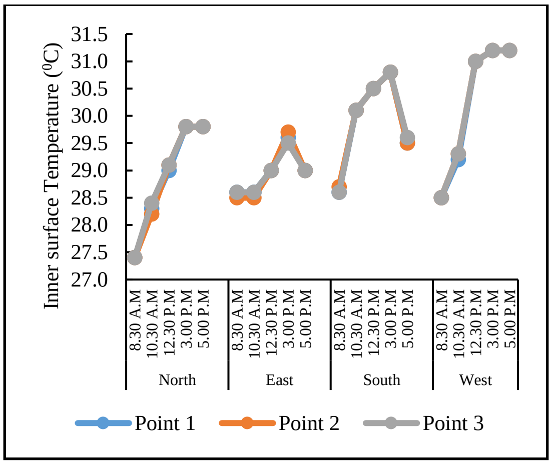
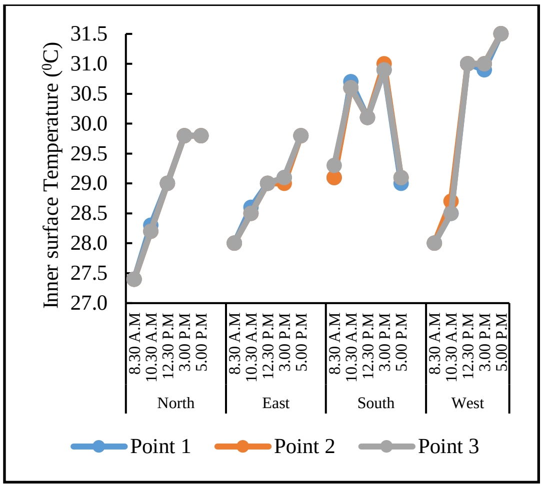


Figure 4.7: Green wall – Ground floor (I)



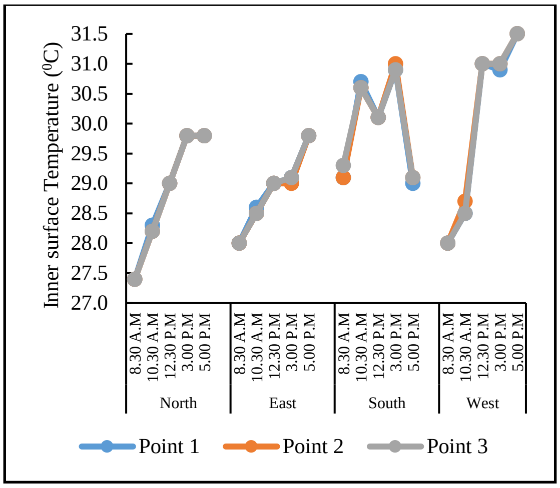
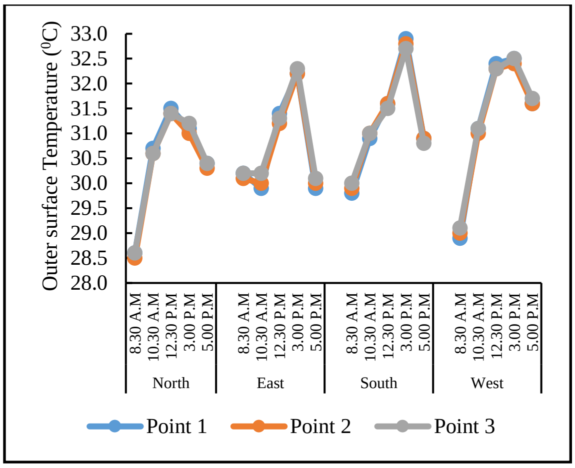


Figure 4.8: Green wall – First floor (I)

Figure 4.9: Green wall – Second floor (I)

The average temperature of the conventional wall - 7th July 2022



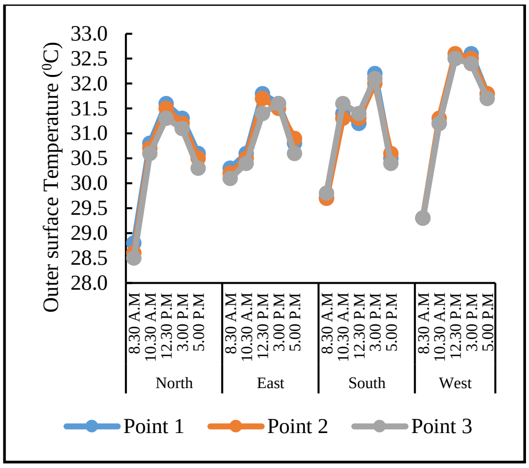
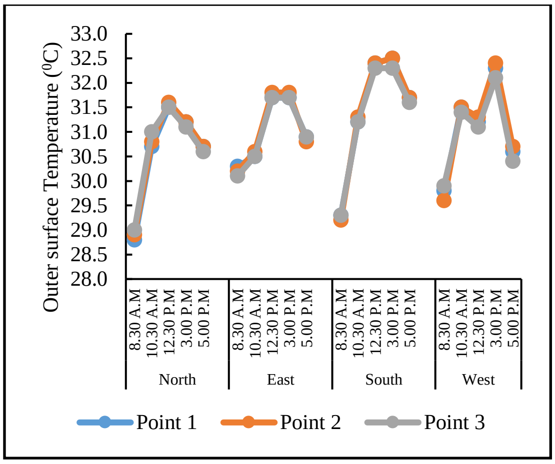


Figure 4.10: Conventional – Ground floor (O)

Figure 4.11: Conventional – First floor (O)



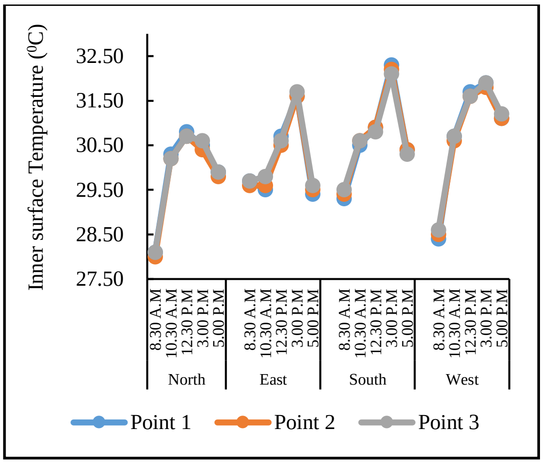
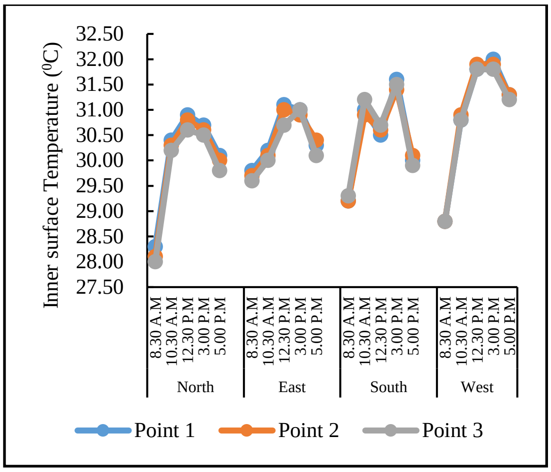


Figure 4.12: Conventional – Second floor (O)

Figure 4.13: Conventional – Ground floor (I)



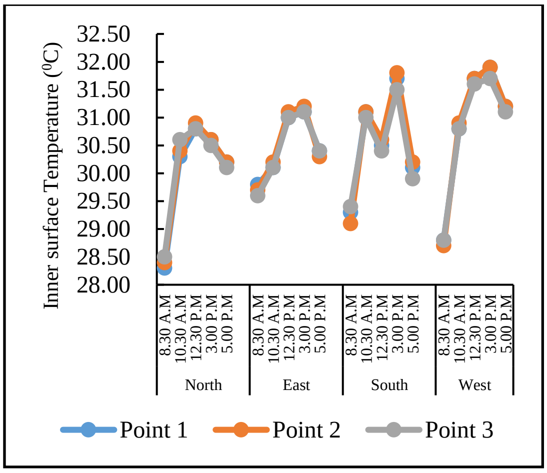


Figure 4.14: Conventional – First floor (I) Figure 4.15: Conventional – Second floor (I)

Note: In the North wall Points 1, 2, and 3 are referred to as A, B, and C. In East wall Point 1, 2, and 3 are referred to as X, Y, and Z. In West wall Point 1, 2, and 3 are referred to as P, Q, and R. In North wall Point 1, 2, and 3 are referred to as D, E, and F.

O – Outer surface; I – Inner surface

As per Figure 4.4 – Figure 4.15, during the morning time slot, the temperature at the East wall is higher on both internal and external wall surfaces of each floor of both buildings while in the afternoon, the West direction shows the highest temperature values. This is due to the general phenomenon of high intensity of solar radiation received East direction before noon with the sunrise and West direction in the afternoon with the sunset.

When it refers to the surface temperature of both internal and external wall surfaces of green and conventional walls, it can be clearly seen that the temperature of conventional walls is always higher than the green wall. Regarding the status of outer surface temperature, the conventional wall shows a maximum of 32.9^{0}C temperature and a minimum of 28.5^{0}C while the green wall shows the 27.5^{0}C - 31.8^{0}C temperature range. When it's come to the internal wall temperature, a maximum of 32.3^{0}C and a minimum of 28.0^{0}C temperature shown in the conventional wall whereas the green wall shows a maximum of 31.5^{0}C and a minimum of 27.4^{0}C temperature.

As observed in Figure 4.4 - Figure 4.15, the temperature measurements of the selected three points slightly differ from each other in every targeted time slot for both internal and external wall surfaces. Therefore, the arithmetic mean of the temperature values of three points was considered as the final temperature for each wall orientation at a particular time using Equation 1. Subsequently, to calculate the average temperature of each day, the geometric mean was used based on the calculated arithmetic mean values of each wall surface at targeted time slots using Equation 2.

Accordingly, the average temperature of each day concerning the four wall orientations of both internal and external wall surfaces of each building was calculated and illustrated in Figure 4.16 – Figure 4.21.

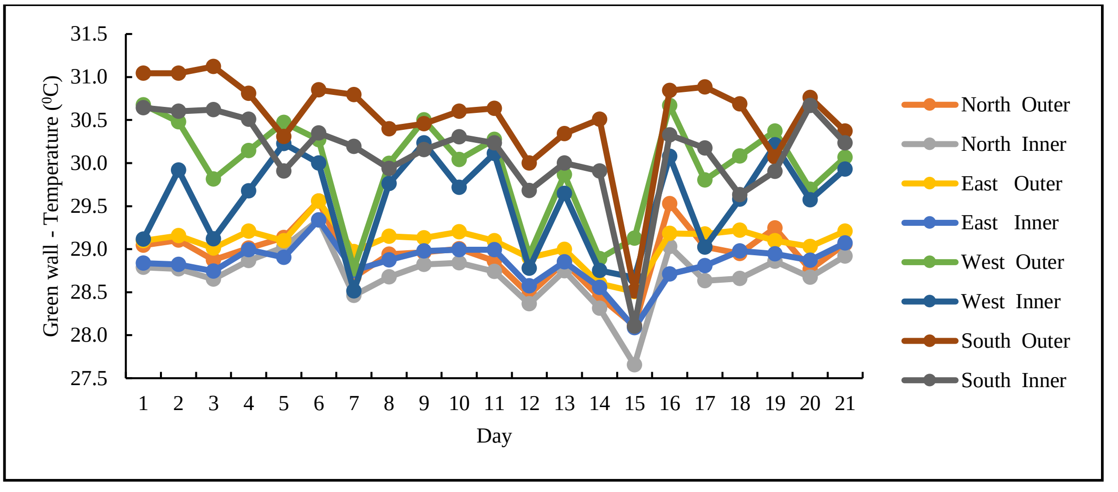


Figure 4.16: Outer and inner surface temperature, Green wall - Ground floor

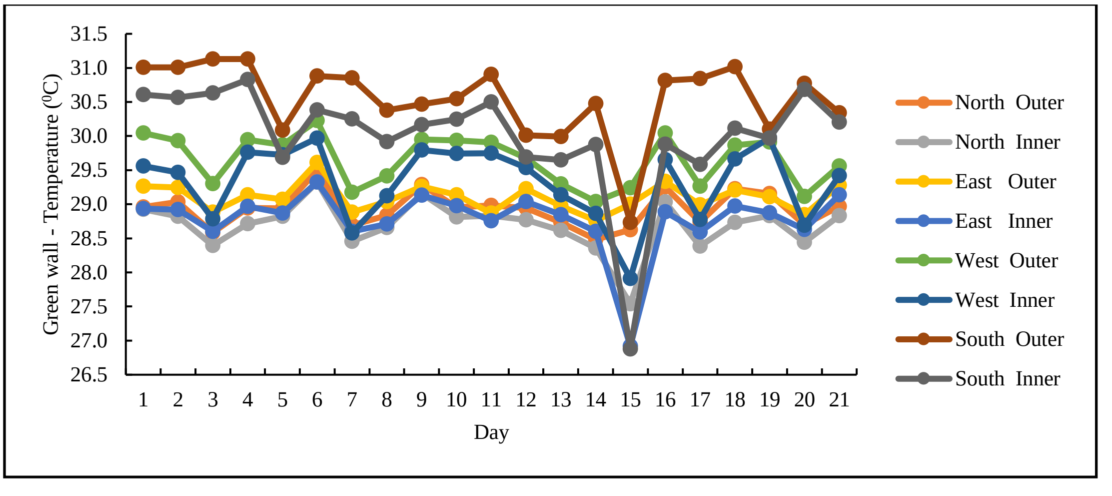


Figure 4.17: Outer and inner surface temperature, Green wall - First floor

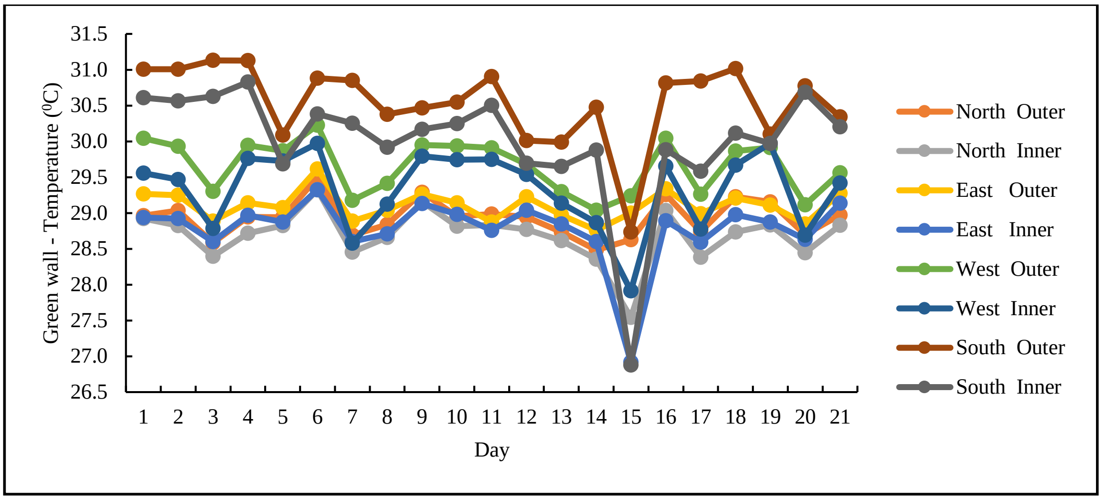


Figure 4.18: Outer and inner surface temperature, Green wall – Second floor

Figure 4.16 – Figure 4.18 illustrates the mean temperature of each day on all three floors of the green wall building. On each floor, temperature values were slightly varied with the wall orientation. As shown in Figure 4.16 – Figure 4.18, the South wall shows the highest temperature and followed by the West, East, and North wall shows the fewer temperature values, respectively. Since there were no surrounding objects which obstruct the green wall building, this can be totally due to the greenery impact. In other words, the absence of uniform plant coverage of the wall surfaces effect the temperature variations of the wall surface. As per collected data, it was revealed that the average foliage thickness of the North wall is 45 cm, the East and West wall are 40 cm, and the South wall is 35 cm. Hence, at first glance, it can be easily concluded that the wall orientation (North wall) which has the high foliage thickness shows the minimum temperature while the wall orientation (South wall) with less foliage thickness accounts for the maximum temperature behaviours.

Figure 4.19 – Figure 4.21 illustrates the average temperature of each day on all three floors of the conventional wall building. Similar to the green wall building, conventional wall building also did not obstruct the surrounding objects. To this end, the temperature values of each wall orientation show similar figures.

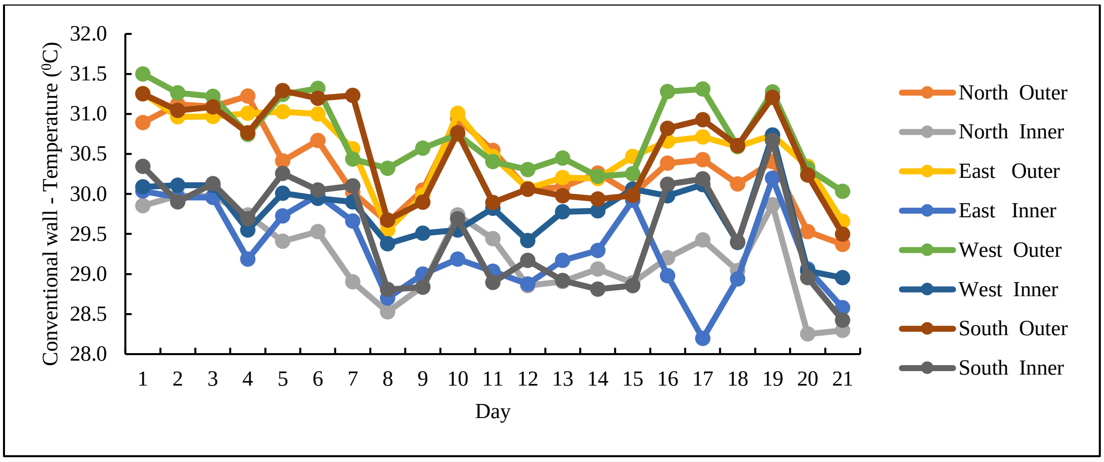


Figure 4.19: Outer and inner surface temperature, Conventional wall - Ground floor

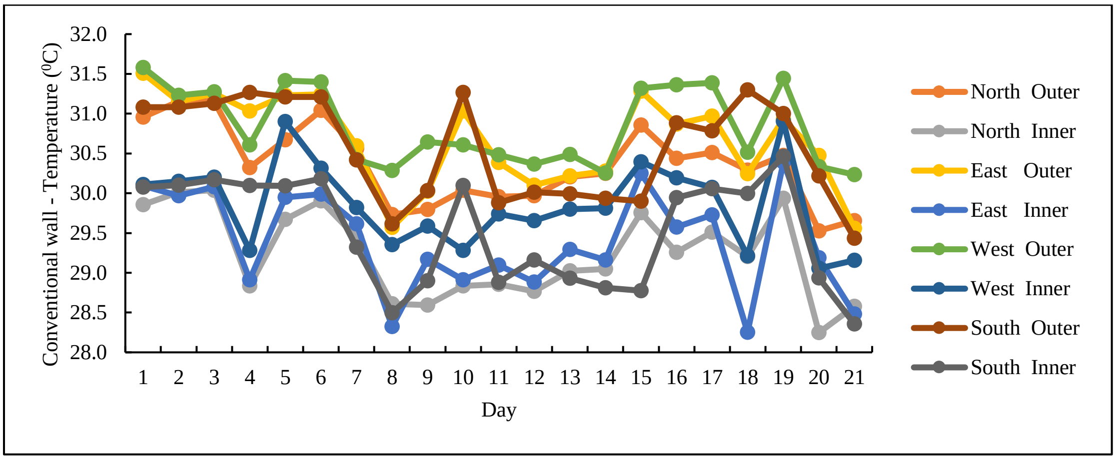


Figure 4.20: Outer and inner surface temperature, Conventional wall - First floor

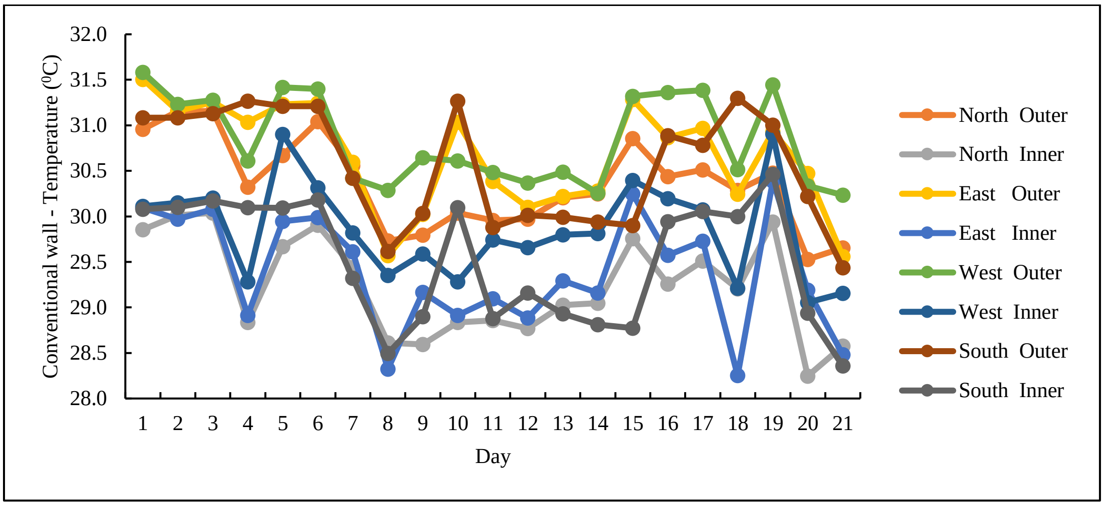


Figure 4.21: Outer and inner surface temperature Conventional wall - Second floor

As observed in Figure 4.16 – Figure 4.21, it is clearly acknowledged that the conventional wall temperature is higher on all occasions compared to the green wall.

Further, it shows that there is no significant variation in the temperature measurements relative to the floors of the green wall building. On the other hand, as shown in Figure 4.16 – Figure 4.21, the magnitude of outer and inner temperature differences of green walls are very less compared to the conventional wall. Outer and inner temperature differences of green walls varied from 0.23^{0}C to 0.53^{0}C and conventional wall shows 0.95^{0}C to 1.27^{0}C temperature variation.

As observed in Figure 4.16 – Figure 4.21, the temperature values of both buildings are successive throughout the study period. In this context, average temperature values for internal and external wall surfaces of both buildings were obtained by considering the temperature figures for 21 days (Refer Appendix B). The summary of the average temperature is shown in Table 4.3.

Table 4.3: Summary of average temperature

Green wall Building – Average Surface Temperature (^{0}C)												
Location	**North Wall**			**East Wall**			**West Wall**			**South Wall**		
	O	**I**	**O- I**	**O**	**I**	**O- I**	**O**	**I**	**O- I**	**O**	**I**	**O- I**
Ground Floor	28.93	28.71	**0.23**	29.08	28.84	**0.23**	29.95	29.55	**0.40**	30.53	30.10	**0.43**
1st Floor	28.93	28.69	**0.24**	29.10	28.78	**0.33**	29.65	29.33	**0.32**	30.55	30.02	**0.53**
2nd Floor	34.23	33.95	**0.27**	34.08	33.79	**0.29**	35.07	34.80	**0.27**	33.88	33.60	**0.27**
Conventional Wall Building – Average Surface Temperature (^{0}C)												
Ground Floor	30.34	29.23	**1.12**	30.54	29.32	**1.23**	30.75	29.77	**0.98**	30.54	29.53	**1.01**
1st Floor	30.36	29.24	**1.12**	30.66	29.40	**1.27**	30.84	29.86	**0.98**	30.56	29.52	**1.04**
2nd Floor	33.24	32.16	**1.08**	33.21	32.23	**0.99**	33.62	32.67	**0.95**	32.83	31.86	**0.96**

Note: O – Outer; I - Inner

As it is clearly understood from Table 4.3, the outer and inner temperature differences are not significantly varied with the floors. However, with regards to the overall magnitude of the difference in temperature values is much more noticeable in the conventional wall compared to the green wall as expected.

4.3.2.3 Heat transfer through external walls

In the next part of the analysis, the heat transfer amount through the building's external walls is taken into consideration by using Equation 3.

Since both buildings consist of block walls, the thermal conductivity of the heat transfer surface was considered as 1.7 W/m^{0}C with respect to the blocks. Heat transfer calculations for both wall surfaces are given in Table 4.4 for 1m^2 of wall area.

Table 4.4: Heat transfer calculations for green wall and conventional wall

Wall Orientation	**Green wall per m^2 (W per hour)**			**Conventional wall per m^2 (W per hour)**		
	Ground Floor	**1st Floor**	**2nd Floor**	**Ground Floor**	**1st Floor**	**2nd Floor**
North wall	2.58	2.74	3.11	12.68	12.72	12.25
East Wall	2.66	3.69	3.33	13.92	14.39	11.19
West Wall	4.48	3.68	3.04	11.10	11.15	10.72
South Wall	4.83	6.03	3.10	11.41	11.78	10.92
Sub Total	**14.55**	**16.14**	**12.58**	**49.12**	**50.04**	**45.08**
Total		**43.27**			**144.23**	

Table 4.4 clearly depicts that the highest heat transfer value is achieved from the conventional wall by approximately 144 W/m^2 per hour while the green wall achieved only about 43 W/m^2 per hour of heat transfer. It is clearly understood from the results that the conventional wall accounts for additional 101 W/m^2 per hour of heat transfer compared to the green wall. To this end, it can be concluded that the green wall has the ability of heat insulation.

In general, heat transfer through the wall surfaces are equivalent to the amount of energy required for heating and cooling purposes. With respect to the current study, the study location belongs to the tropical rainforest climate. Hence, mainly, the energy is required for cooling purposes. To this end, in this study, the energy required for cooling purposes for the unit area of the wall is 144 Wh and 43 Wh for conventional walls and green walls, respectively. Hence, it is clear that the energy required for cooling purposes is much more noticeable in the conventional wall compared to the green wall.

4.3.2.4 Energy cost calculation

As per the calculation in Sub-section 4.3.2.3, the total energy requirement for the cooling purposes of each building was calculated by assuming that the same temperature existing in every day throughout the month, as given in Table 4.5.

Therefore, the energy required for the cooling purposes of each building that is shown in Table 4.5 can be considered the minimum energy requirement.

Table 4.5: Energy requirement for the cooling purpose of total building

Description	Green wall building	Conventional wall building
per hour (W/h)	8,302.85	33,698.54
per day (W)	74,725.65	303,286.89
per month (W)	2,241,769.64	9,098,606.71
per month (kW)	2,241.77	9,098.61
Per month (kW /m^2)	9.07	38.94

Table 4.5 evidence that the energy required for the cooling purpose of green wall building is lesser compared to the conventional wall building. This is due to the effect of the heat transfer through the external wall surfaces. In green wall building, the plant layer acts as a heat insulator and maintains less heat transfer through the wall surface compared to the conventional wall. This is result in 70% of energy cost saving per unit wall area of a green wall in comparison to the conventional wall.

As the next step, the cost for the required energy was calculated based on the calculated energy requirement in Table 4.5. Energy cost was calculated based on the tariff plan published by Ceylon Electricity Board (CEB) 2022 for hotel purposes. As per the CEB tariff plan, the selected two cases belong to the H1 customer category because each individual point of supply is delivered and metered at 400/230V nominal and where the contract demand is less than or equal to 42 kVA. Accordingly, 21.50 LKR/kWh of energy charge and 600 LKR/month of fixed charge are applicable. For this H1 customer category, there is no maximum demand charge for the month. To this end, the annual energy cost for the cooling purpose of both buildings presents in Table 4.6.

Table 4.6: Annual energy cost for the cooling purpose of both buildings

Description	Green wall building	Conventional wall building
Energy requirement per month (kW)	2,241.77	9,098.61
Energy charge (LKR/kW)	21.50	21.50
Fixed charge (LKR/month)	600.00	600.00
Total (Per Month) (LKR)	**48,798.05**	**161,255.60**
Per m^2 (LKR)	**197.43**	**471.51**
Total (Per Annum) (LKR)	**585,576.57**	**1,935,067.19**
Per m^2 (LKR)	**2,369.12**	**5,658.09**

As per Table 4.6, it is clear that the green wall can save the 3,975.33 LKR per unit wall area annually compared to the conventional wall. In other words, the presence of a green layer on the external wall surfaces can save a minimum of 70% of energy cost for cooling purposes in the tropical climate.

4.3.3 Life cycle cost analysis: Green vs Conventional wall

To assess the LCC of green walls in comparison to a conventional wall, the costs associated with the initial, maintenance, and disposal phases have been quantified to carry out the LCC comparison of the conventional wall and green wall. Due to the unavailability of drawings, onsite measurements were taken to obtain the external dimension of both buildings. Further, cost data for each phase were obtained by referring to log books and the market survey. The costs associated with each life cycle phase have been quantified as follows (Refer Appendix C for further details of cost breakdowns).

4.3.3.1 Initial cost

Cost of block wall construction, internal and external finishes, doors, and windows are similar components of both the conventional and green walls buildings. In addition, the selected green wall building has the costs related to the taking care of plants, preparation of growing media, and preparation, transportation, and installation of support structure as initial costs (Refer Table 3.5 - LCC stages and components of green walls). Table 4.7 illustrates the initial cost details of the green wall and the conventional wall.

Table 4.7: Summary of the initial cost of the conventional wall and green wall

Cost Component	Green wall (LKR)	% of total	Conventional wall (LKR)	% of total
	Block Wall			
Block wall	574,732.58	13%	699,815.09	16%
Internal finishes				
Internal plastering	262,954.99	6%	323,596.70	7%
Internal painting	82,927.49	2%	102,051.92	2%
External finishes				
External plastering	178,208.12	4%	216,992.63	5%
External painting	102,481.06	2%	124,784.63	3%
Doors and windows	2,994,417.90	68%	2,994,417.90	67%
Total initial cost excluding vegetation	**4,195,722.15**	96%	**4,461,658.88**	100%
Total initial cost per m^2 excluding vegetation	**12,268.19**		**10,776.95**	
				Green Wall
Obtaining and taking care of plants	1,800.00	0.04%	-	
Preparation of growing media	2,000.00	0.05%	-	
Preparation of Support structure	135,952.83	3%	-	
Transportation and installation of the support structure	56,547.62	1%	-	
Total initial cost of vegetation	**196,300.45**	4%	**-**	
Total initial cost per m^2 of vegetation	**1,721.93**		**-**	
Total Initial Cost	**4,392,022.60**	100%	**4,461,658.88**	100%
Total Initial Cost (per m^2)	**12,842.17**		**10,776.95**	

As observed in Table 4.7, the green wall contributes to a higher initial cost compared to the conventional wall due to the presence of green vegetation. This results in a 19% cost-saving on the conventional wall. When considering the green wall, 96% of the total initial cost accounts for the block work construction, and the remaining 4% is responsible for the green layer. However, in the conventional wall, the whole 100% is account for the block work.

4.3.3.2 Maintenance cost

Maintenance for internal and external paintings, doors and windows, and minor repairs are similar maintenance cost components of both the conventional and green walls buildings. Though the literature review identified many more maintenance cost components for the green wall (Refer Table 3.5 - LCC stages and components of green walls), as per the construction of this selected green wall, maintenance activities are mainly limited to taking care of plants and pruning. The plant species (*Thunbergia* *laurifolia*) used for the green wall construction is well adapted to this environment. As a result of that, frequent watering is not needed, and since there is no irrigation system, no need for pipe replacements. The support structure is made up of timber and finished with wood preservatives. Hence, as per the building owner's opinion, timber structures can exist for more than fifty years.

Maintenance cost details of selected two buildings including time intervals are explained in Table 4.8.

Table 4.8: Summary of maintenance cost details of green wall and conventional wall

Cost Component	Amount (Per one time)	Time interval	Source
Conventional wall			
Redecoration Cost (Internal and External painting)	226,836.56	Every 2 years	Building owner
Replacement cost (Doors and Windows)	2,994,417.90	Every 40 years	Asif et al. (2005)
Minor repairs	60,000.00	Every 20 years	Building owner
Green wall			
Redecoration Cost (Internal painting)	82,927.49	Every 2 years	Building owner
Redecoration Cost (External painting)	102,481.06	Every 5 years	Building owner
Replacement cost (Doors and Windows)	2,994,417.90	Every 40 years	Asif et al. (2005)
Minor repairs	60,000.00	Every 20 years	Building owner
Care taking of plants	1,800.00	Every month for the first 3 months	Building owner
Pruning	3,000.00	Every 6 months after the first year	Building owner

As seen in Table 4.8, the considered green wall building has additional maintenance costs related to taking care of plants and pruning compared to the conventional wall. Further, when regards the redecoration cost details, in conventional walls both internal and external paintings are usually done every two years. However, in green wall building, internal painting needs to be done every two years and external painting needs to be done every five years. This is because the green layer behind the green wall covers the wall surface from direct sunlight and other natural effects that can harm the wall surface. Hence, it could be a long-term cost saving for green wall building. It is further evidence that the green walls have the ability to increase façade durability as discussed in Sub-section 3.4.1.

4.3.3.3 End life cost

There is no clear idea about the disposal cost of green walls as well as the conventional wall from the building owner's side. Hence, the decision of whether disposal cost is considered or not for the LCC analysis was made based on the literature review.

To this end, as discussed in Sub-section 3.6.2.3, the disposal cost contribution of any green wall type to the whole LCC is about 1%. Hence, disposal costs of green walls could be ignorable when considering the LCC. On a similar note, Heralova (2018) stated that the contribution of the disposal cost of a building to its LCC is considerably low. Therefore, it is clear that the disposal cost of the wall is also similar. Hence, the disposal cost of both green and conventional wall were excluded in the analysis of LCC.

4.3.3.4 Life cycle cost calculation

As stated in Sub-section 2.10.2.2, the LCC calculation was done based on the 4.99% discount rate and forty years of a lifetime for both green and conventional walls. In this calculation, assumed that the lifetime of walls is similar to the lifetime of the building. Since the wall area of both building profiles is different, NPV was calculated for the square meter. Accordingly, the LCC of both green and conventional walls was calculated while considering the costs associated with initial, maintenance, and energy cost for cooling purposes. Table 4.9 and Table 4.10 illustrates the LCC calculation of the both conventional wall and green wall, separately.

Table 4.9: LCC calculation of the conventional wall

Time	Description	Value (LKR)	Discount Rate 4.99%	PV (LKR)
Initial cost				
0	Initial Cost	4,461,658.88	1	4,461,658.88
Total Initial cost (NPV)				**4,461,658.88**
Total Initial cost per m^2 (NPV)				**10,776.95**
Maintenance cost				
2nd, 4th, 6th, 8th, ……..…., 36th, 38th	Redecoration Cost (Internal and External)	226,836.56	8.24	1,868,063.12
40th	Replacement Cost	2,994,417.90	0.00	-
20th	Repairing Cost	60,000.00	0.38	22,640.14
Total Maintenance cost (NPV)				**1,890,703.26**
Total Maintenance cost per m^2 (NPV)				**4,566.92**
			Total NPV	**6,352,362.14**
			Total NPV per m^2	**15,343.87**
Energy cost				
1 - 40 years	Energy Cost	2,354,640.53	17.17	40,437,871.36
Total Energy cost (NPV)				**40,437,871.36**
Total Energy cost per m^2 (NPV)				**97,676.02**
			Total NPV including energy cost	**46,790,233.50**
			Total NPV per m^2	**113,019.89**

Table 4.10: LCC calculation of the green wall

Time	Description	Value (LKR)	Discount Rate 4.99%	PV (LKR)
Initial cost				
0	Block Wall	4,195,722.15	1	4,195,722.15
0	Green wall	196,300.45	1	196,300.45
Total Initial cost (NPV)				**4,392,022.60**
Total Initial cost per m^2 (NPV)				**12,842.17**
Maintenance cost				
2nd, 4th, 6th, 8th, …, 36th, 38th	Redecoration Cost (Internal)	82,927.49	8.24	682,931.32
5th, 10th, 15th, 20th, 25th, 30th, 35th	Redecoration Cost (External)	102,481.06	2.97	303,959.75
40th	Replacement Cost	2,994,417.90	0.00	-
20th	Repairing Cost	60,000.00	0.38	22,640.14
1/12th, 2/12th,3/12th	Care taking of Plants	1,800.00	2.98	5,356.35

1.5th, 2nd, 2.5th, 3rd, 3.5th,4th,4.5th,........... ...., 39th,39.5th	Pruning	3,000.00	32.70	98,100.66
Total Maintenance cost (NPV)				**1,112,988.22**
Total Maintenance cost per m^2 (NPV)				**3,254.35**
			Total NPV	**5,505,010.82**
			NPV per m^2	**16,096.52**
Energy cost				
1st	Energy Cost	1,935,067.19	0.95	1,843,030.17
2 - 40Years	Energy Cost	585,576.57	17.03	9,973,135.95
Total Energy cost (NPV)				**11,816,166.11**
Total Energy cost per m^2 (NPV)				**34,550.19**
			Total NPV including energy cost	**17,321,176.94**
			NPV per m^2	**50,646.72**

As shown in Table 4.9 and Table 4.10, the NPV value of the initial cost is higher in the green wall compared to the conventional wall. As pointed out in Sub-section 4.3.3.1, this is due to the presence of plant and support structures. It is clear that 19% of the initial cost is higher than the green wall compared to the conventional wall.

When considering the maintenance cost, the NPV value is higher in the conventional wall compared to the green wall. At the first glance, it is clear that the green wall has more cost components compared to the conventional wall. However, this higher maintenance cost of conventional walls occurred due to the time interval difference between external paintings of green walls. As defined in Sub-section 4.3.3.2, the external painting time interval of the conventional wall is two years and five years for the green wall. To this end, the green wall has a 29% lesser cost compared to the conventional wall.

In the energy cost calculation for the LCC analysis, the energy cost for the green wall in the first year was considered as a similar magnitude to the energy cost of the conventional wall due to the plant had taken approximately one year for the full coverage of the wall surfaces of the building. Calculation results revealed that the conventional wall has a 65% higher energy cost for cooling purposes compared to the green wall based on the considered life span.

Table 4.11 clearly illustrates the summary of the LCC calculation of both green walls and conventional walls with the cost saving.

Table 4.11: Summary of LCC between the green wall and conventional wall

Cost	LKR/ m^2 (PV)		Green wall cost impact
	Green wall (GW)	Conventional wall (CW)	$\frac{\text{PV of GW} - \text{PV of CW}}{\text{PV of CW}} \times 100\%$
Initial	12,842.17	10,776.95	19%
Maintenance	3,254.35	4,566.92	-29%
NPV without energy	**16,096.52**	**15,343.87**	**5%**
Energy	34,550.19	97,676.02	-65%
NPV with energy	**50,646.72**	**113,019.89**	**-55%**

According to the above equation in Table 4.11, positive impacts are savings to the conventional wall whereas negative impacts are actual savings to the building which has the green wall. As seen in Table 4.11, if energy cost was not considered, the conventional wall can save 5% of the cost over the life span. However, with the consideration of energy cost, green walls can save 55% of the cost of the conventional wall over the same life span. In this context, it was clear that the negative effect of the high initial cost of the green wall compared to the conventional wall can be offset by considering the energy cost-saving benefit of the green wall.

4.3.4 Sensitivity analysis

As the next step of the analysis, a sensitivity analysis was performed considering alternative analysis periods and discount rates to assess the sensitivity of the results to different values of the independent variables (analysis period and discount rate) (Refer Appendix D for calculations).

By considering the alternative years of 30, 40, and 50 years, sensitivity analysis was performed for both profiles while other factors are constant and given in Figure 4.22.

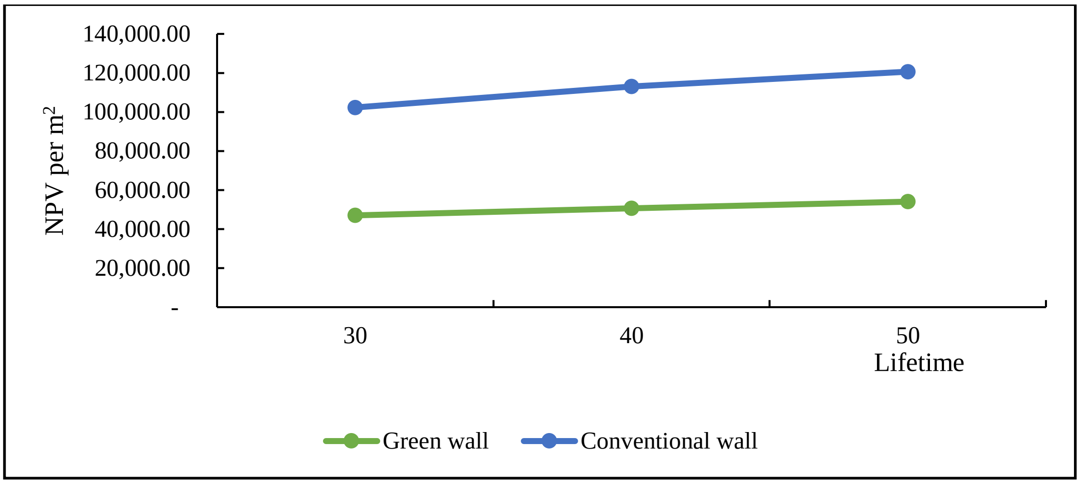


Figure 4.22: LCC vs lifetime of green walls

As per Figure 4.22, the total NPV shows direct proportionate to the lifetime. In other words, the total NPV of both profiles increases with their lifetimes. Especially, sensitivity analysis (Figure 4.22) revealed that in every considered possible lifetime LCC of a green wall is lesser compared to the conventional wall.

In addition, again sensitivity analysis was conducted by changing the discount rates of 4.76%, 4.99%, and 5.20% to validate the results obtained in the above circumstances and given in Figure 4.23.

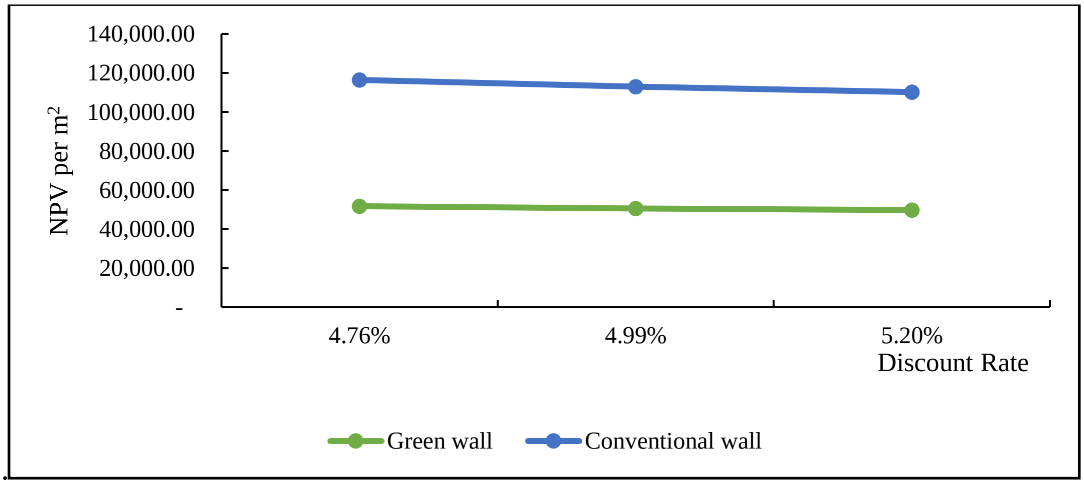


Figure 4.23: LCC of green wall vs discount rate

Figure 4.23 shows that the total NPV of both profiles is inversely proportionate to the discount rate. Hence, the LCC of the wall surfaces decreases with the increment of the discount rate. However, it is clear that at every discount rate, the LCC of the green wall is lesser compared to the conventional wall.

4.4 Chapter Summary

This chapter discussed a detailed analysis of gathered data through a preliminary survey and case studies. Through the findings from the preliminary survey, green wall applications in Sri Lanka were comprehensively identified under three main categories namely green wall type, green wall placement, and the green wall applied properties. Finally, a preliminary survey was helped to identify suitable cases for the case study analysis. The case selection criteria and procedures are also presented with the justifications. A detailed analysis of the thermal behaviour of the green wall compared to the conventional wall was performed based on the selected case study profile. At the same time, the energy cost-saving potential of green walls in comparison to the conventional wall is also evaluated. In the latter part of the analysis, with the aim of achieving objective 4, LCC analysis was performed to assess the LCC of the green wall compared to the conventional wall based on the selected cases. By further strengthening those findings, sensitivity analysis was also carried out to validate the LCC analysis findings with the possible lifetimes and the discount rates.

CHAPTER FIVE

RESEARCH FINDINGS AND DISCUSSION

CHAPTER FIVE

5. RESEARCH FINDINGS AND DISCUSSION

5.1 Introduction

This chapter presents the synthesis of findings derived from the analysis performed and the literature review. The synthesis includes green wall application in Sri Lanka, the thermal and energy saving performance, and finally the overall economic performance of green walls in comparison to a conventional wall. Then, a summary is given highlighting the main points discussed in this chapter.

5.2 Green Wall Applications in Sri Lanka

The data collected through the preliminary survey confirmed that green wall application is propagated to some extent in the Sri Lankan context. During the literature review, it was identified that global literature evidenced that there exists three main types of green walls based on their construction method; Direct green façade, indirect green façade, and living walls (Refer Sub-section 3.3). Amongst seems that green façade is the most commonly available green wall type. However, there was no indication whether direct or indirect. In line with that current study as well as Rupasinghe and Halwathura (2020) indicated that green walls available in the Sri Lankan context also fall into the above identified three categories. Of them, indirect green façade is the most commonly available green wall type in Sri Lanka. Further, the current study along with Rupasinghe and Halwathura (2020) confirmed that direct green façade type is mostly applied to boundary walls with the intention of aesthetic appearance. When considering green wall applications in different properties, a preliminary survey carried out in the current study and Rupasinghe and Halwathura (2020) show that green walls are used in different constructions including hotels, residential, offices, as well as industrial buildings.

Though green wall application is extended to a reasonable level in Sri Lanka, most of the building owners have incorporated this green wall concept into their buildings with limited awareness and knowledge about its potential, with the primary intention of obtaining the aesthetic appearance and making the building's outer skin green.

5.3 Thermal Performance: Green vs Conventional Wall

The thermal performance of green walls was assessed by considering the temperature differences between internal and external wall surfaces of green and conventional buildings. Accordingly, the thermal performance of green walls in the Sri Lankan context is somewhat equivalent to its performance in some countries while it differs from some other countries.

As evidenced in studies by Eumorfopoulou and Kontoleon (2009), Sternberg et al. (2011), Perini et al. (2011), Susorova et al. (2014), and Olivieri et al. (2014), representing Greece, England, Netherland, United State of America, and Spain, respectively (Refer Table 3.6 – Table 3.8), in Sri Lankan context also the exterior façade surface temperature reduction of the green wall is less compared to the conventional wall (Refer Table 4.4). The above studies have been carried out in different climate conditions with a focus on different types of green walls. Hence, it can be concluded that irrespective of climate conditions and green wall types used, green walls contribute to less heat transfer through exterior facade surfaces to the interior of the building, in comparison to a conventional wall. However, the amount of heat transfer may vary with the country/climate, green wall types and the plant species used, the plant foliage thickness, and the like.

According to Perini et al. (2011), Šuklje et al. (2013), Jim (2015), Cameron et al. (2014), and Pérez et al. (2011), the amount of temperature reduction through exterior surfaces has ranged from 2.7^0C, 4^0C, 5^0C, 9.9^0C, and 15.2^0C, respectively where the buildings have used only a particular type of green wall, indirect green facades. However, as per the current study, there was no such significant temperature reduction observed. The difference was only 1.1^0C. When considering the results of Cameron et al. (2014) and Pérez et al. (2011), the temperature reduction is significantly high compared to other studies as well as the current study. Cameron et al. (2014) considered the period of August to September which had Cfb climatic conditions according to the Koppen Classification for temperature assessment in England whereas Pérez et al. (2011) assessed the temperature behaviour in Spain, having Csa climatic conditions throughout the whole year. When considering the studies of Perini et al. (2011), and Šuklje et al. (2013), though the climatic conditions are similar (Cfb), the studied period and the plant species used for the study were different (Refer Table 3.7). To this end, it can be concluded that the temperature reduction potential of green walls did not completely depend on the green wall type, it can vary with climatic conditions, plant species used as well as the foliage thickness.

It can be further evidenced by referring to the current study and Wong et al. (2010). The current study and Wong et al. (2010) directed research on indirect green façades under Af climatic conditions and presented a 1.1^{0}C and 4.4^{0}C temperature reduction, respectively. Though the climatic condition and the green wall type are similar in the above two contexts, the result shows a notable difference. Since there is no indication about the plant species used and the foliage thickness, it is safe to conclude that the difference could be due to the plant species used and foliage thickness. However, Madushika (2020), showed a 1.15^{0}C of average temperature reduction of indirect green façade with steel structure where having *Thunbergia laurifolia* in tropical rainforest climate. Since the boundary conditions of the current study and Madushika (2020) are similar, the reason for the additional 0.05^{0}C temperature reduction is the support structure difference.

On another note, various studies (Table 3.6 – Table 3.8) have identified foliage thickness as one of the reasons that can affect the thermal performance of the green walls. It was further proved through the results of the current study. As mentioned in Sub-section 4.3.2.2, the green wall with high foliage thickness showed a minimum temperature difference and vice versa. For example, in the current study, the average foliage thickness of the North wall is 45 cm while the East, West, and South contained 40 cm, 40 cm, and 35 cm thicknesses, respectively. Table 4.3 evidenced that the North wall had a temperature reduction of 0.25^{0}C while the respective values for East, West, and South were 0.32^{0}C, 0.23^{0}C, and 0.41^{0}C. A similar conclusion was derived by Sternberg et al. (2011), having 10 cm foliage thickness showed a 9.5^{0}C temperature reduction while 1.7^{0}C was attributed to foliage thickness of 45 cm. These surface temperature reductions further confirm another attribute that green walls can act as heat barriers or heat insulators.

5.4 Energy Saving: Green vs Conventional Wall

The temperature differences of green walls result in energy-saving. According to current study findings, green walls contribute to nearly 70% of energy savings for cooling purposes. The results of the current study coincide with some other findings of previous studies. For example, a simulation study carried out considering main cities in the United Kingdom (UK), Canada, Russia, Greece, China, Saudi Arabia, India, and Brazil concluded that the energy-saving potential of green walls can vary significantly, from 90% to 35% (Alexandri & Jones, 2008).

Further, Pan and Chu (2016) found that green walls contribute to 16% of energy consumption reduction for air conditioning from August to September in Hong Kong. Even though Hong Kong belongs to the Asian region, the results of this study show notable differences when compared to the current study. The considered study periods, green wall type, plant species used, and foliage thickness in both scenarios are different. Hence, it can be pointed out that the energy-saving benefits vary with the methodology adopted in the study, plant species, green wall type, foliage thickness, etc.

On another note, Coma et al. (2017) assessed that the indirect green façades can save up to 34% of energy during the cooling season in Spain, while Cameron et al. (2015) showed a 40 – 50% of energy efficiency due to the implementation of indirect green facades in the UK. However, the energy saving of green walls in the Sri Lankan context in the current study is higher compared to the above scenarios. The reason can be the consideration of seasonal changes in European countries and not in the Sri Lankan context due to the absence of such significant seasonal variations. Hence, it can be concluded that, though the green wall type is similar, energy performance can be varied with the region/climate.

According to Madushika (2020), an indirect green façade with a steel structure shows 64% of the energy saving for cooling purposes while the current study shows 70% of energy cost savings. Support structure difference of two indirect green façade systems can be considered as the reason for this additional 6% cost saving of indirect green façade with timber structure.

Further, according to the collected and analysed data, the relationship between the energy-saving amount of green walls and foliage thickness can be evaluated. For example, the energy saving of North, East, West, and South walls are reduced from 30 Wh to 20Wh (Refer Table 4.4) whereas the foliage thickness is reduced from 45cm to 35 cm (Refer Sub-section 4.3.2.2). Since all other factors that affect the energy-saving potential of green walls are constant, it is clear that the energy-saving potential is varied with the foliage thickness.

5.5 Economic Performance: Green vs Conventional Wall

As mentioned in Sub-section 3.5 - Challenges for green wall application, Wong et al. (2010) and Chew and Conejos (2016) identified that the high initial cost of green walls is a major hindrance to adapting the green wall concept. To support this, the current study along with previous findings shows that the initial cost of the green wall is higher than the conventional wall. According to the case study analysis of the indirect green façade considered in the study (Sub-section 4.3.3.1), the initial cost per unit of green wall is 19% (LKR 12,842.17) higher than an equal area of the conventional wall (LKR 10,776.95). The additional cost of 19% is for the construction of the green layer and support structure of the green wall. However, Madushika (2020), pointed out that the considered green wall accounts for an additional cost of 15% for the construction of the green layer and support structure of the green wall. Though the above two studies considered the indirect green façade type with the same plant species of *Thunbergia laurifolia*, the material involvement for the support structure is different. Hence, it can be concluded that the initial cost contribution can vary with the material used for the support structure. Conversely, the results of Rajamanna (2019), a direct green façade can save 29% of the initial cost compared to a conventional wall due to the absence of support structure and the external surface decoration cost.

When considering the maintenance cost, green walls involve more cost components than conventional walls. Although the literature review identified a range of maintenance cost components regarding green walls (Refer Table 3.5), as per the selected case in this study, care taking of plants and pruning are the only maintenance cost components that are considered. At first glance, it seems like the maintenance cost of the green wall is also higher compared to the conventional wall due to having more cost components (Refer Table 4.8). However, with regards to the present value of per unit wall area maintenance cost, a green wall is LKR 3,254.35 while the equivalent cost of the conventional wall is LKR 4,566.92. This results in 29% of savings in maintenance costs when implementing green walls due to the less frequent requirement of painting for external wall surfaces with the presence of a green layer. Similarly, Madushika (2020) concluded that the green wall can save 23% of additional maintenance costs compared to the conventional wall due to the minimum external painting redecoration time interval. As per Rosasco (2018), if the time for external finishing renovation of the façade without plants is "t", with the same cost, the time for external finishing renovation of green wall is "t"+"n", where "n" is generally 10-15 years. However, the current study and Madushika (2020) considered the period of 5 years as additional for external painting renovation of the wall with the green surface, as per climate, plant species used, and foliage thickness of the local context.

In contrast, some previous studies have concluded that the maintenance cost of green walls is higher compared to the conventional wall (Wong et al., 2010; Chew & Conejos, 2016). As stated in the preceding paragraph the reason for increased maintenance is due to more components involved in the green wall.

As per the selected case study, the maintenance cost of the green wall contributes only a 20% to its LCC. As stated in Sub-section 3.6.2.2, Perini and Rosasco (2013) concluded that on average maintenance costs contribute 51%–78% in all three green wall types. Further, Huang et al. (2019) indicated that maintenance costs slightly vary with the type of green wall system used where it had 84%, 81%, and 74% of contribution respectively, for the carrier system (Living wall), planter system (Indirect green façade with pot), and the support system (Indirect green façade with frame and mesh). The above two studies considered cladding renovation, pipe renovation, irrigation, and plant replacement as the maintenance cost components while the current study consisted of care taking of plants and pruning as maintenance cost components.

In terms of total LCC including initial and maintenance costs, analysis results revealed that conventional walls can save approximately 5% compared to the green wall. This is due to the high initial cost of green walls. Overall, when considering the LCC with the energy-saving benefit, a green wall can save 55% of the cost over the conventional wall. In other words, the energy cost saving of green walls can offset the increased initial cost.

5.6 Chapter Summary

This chapter has synthesised the findings derived throughout the study in terms of green wall applications in Sri Lanka, thermal performance assessment of green walls in comparison to conventional wall, energy saving perspective of green walls, and economic performance assessment of green walls in comparison to conventional wall. The findings of the current study were in relation to the results of the previous studies. Accordingly, in line with the global application, all green wall types are commonly used in all types of buildings including hotels, residential, offices, industrial, educational, hospitals, and religious. In terms of thermal performance, it can be concluded that extend of heat transfer may vary with the country/climate, green wall types and the plant species used, the plant foliage thickness, and the like. Since the energy-saving potential of green walls also derived from the temperature differences, the energy performance also depends on above factors. Finally, the economic performance assessment of green walls evidences that the energy cost saving of green walls can offset the increased initial cost.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

CHAPTER SIX

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

This chapter presents the conclusions derived from the discussion on findings of the literature review and data analysis presented in the preceding chapters. Initially, conclusions derived are discussed through the achievement of objectives. The chapter further focuses on recommendations of the study to green wall practitioners to enable them to enhance the green wall application. The contribution of the study to knowledge and practice was further highlighted in this chapter. In addition, certain limitations that were uncounted during the study are also discussed along with further research directions.

6.2 Accomplishment of Objectives

The research aim of assessing the LCC of green walls with reference to energy-saving potential towards enhancing the adaptation of the green wall concept was achieved through the accomplishment of four main objectives of the study.

Objective 01: To critically review the green wall application in the global context: types of green walls, and their costs and potential benefits

This objective was achieved through a narrative and systematic review and systematic review of extended literature. A narrative review indicates that there are three main alternative types of green walls in practice; direct green facades, indirect green façades, and living walls (Sub-section 3.3). These types of green walls can offer benefits in terms of economic, social, and environmental; building energy savings, greywater treatment, in-service life, increase building durability, increase property value, improvement of air quality, noise reduction, mitigating UHIE, biodiversity, sound transmission reduction, health benefits, habitat creation, aesthetic value, and recreational use of space (Sub-section 3.4) in general. Although green walls offer above benefits, the wide spread of green wall application it is hindered by several factors which includes lack of technical information, breading unwanted pests, high technology, less public awareness, lack of investment capacity, weak legislation and environmental policies, high initial and maintenance costs, etc. (Sub-section 3.5). Amongst, the high initial and maintenance costs of green walls are identified as major barriers towards green wall application.

To this end, as the next step, a systematic review of the economic performance of green walls was conducted (Sub-section 3.6) and identified that a direct green façade is economical in terms of LCC while living walls are the most expensive. This is due to the materials involved in the construction of a direct green façade are comparatively less than the living walls. However, with the variation of the materials involved in the different green wall systems, especially indirect and living wall types, the total cost can change. Though the cost of green walls increases with direct, indirect, and living walls, as per the literature review, living walls are responsible for gaining more economic benefit compared to direct and indirect green façades. Further, the systematic review determined that the annual maintenance cost of green walls consumes a large share of the LCC of any type of green wall, and most of the time annual benefits of green walls offset the cost incurred from initialisation to disposal of a green wall system. Compared to the maintenance cost of the system, the contribution of initial and disposal costs is less.

Objective 02: To identify the green wall applications in Sri Lanka

The second objective was accomplished primarily through a preliminary survey. As per the findings, all three green wall types; direct green facades, indirect green façade, and living walls are available and practiced in Sri Lanka (Sub-section 4.2.1). Among those three types, as per the selected sample, indirect green façade is the most commonly available green wall type. Green wall application is scattered in all types of buildings including hotels, residential, offices, industrial, educational, hospital, and religious buildings. However, most hotel buildings have limited their applications to boundary walls and with direct green façade type to serve the purpose of aesthetic appearance. Further, the living wall type was seen on internal walls while the indirect green façade type was on to exterior wall surfaces of the building.

Objective 03: To assess the thermal performance of green walls in comparison to identical conventional walls

This objective was achieved through case study findings. Initially, surface temperature measurements were obtained from the interior and exterior wall surfaces of each green and conventional building. As per the findings, it was clear that on all occasions, in terms of floors and the wall orientation external and internal wall surface temperature reduction is higher in the conventional wall than in the green wall. On average green wall shows 0.32^0C temperature reduction and the conventional wall shows 1.06^0C temperature reduction. The analysis further revealed that the temperature behaviour of green walls differed from the foliage thickness. The greatest temperature reduction was observed on the points where foliage thickness is less and vice versa.

In the next step heat transfer through each wall surface was calculated and identified that the conventional wall accounts for additional 101 W/m^2 per hour of heat transfer compared to the green wall (Sub-section 4.3.2.3). By considering the heat transfer values and CEB tariff for 2022, the minimum monthly energy requirement for cooling purposes of green wall building was identified as 2,241.77 kWh and for the conventional wall, it was 9,098.61 kWh. This additional 6,856.84 kWh energy requirement of conventional walls results in saving the cost of 3,975.33 LKR per unit wall area annually for green walls. In other words, the presence of a green layer on the external wall surfaces can save a minimum of 70% of energy cost for cooling purposes.

Objective 04: To assess the life cycle cost of green walls in comparison to identical conventional walls.

The fourth objective was also accomplished through case study findings. LCC analysis was performed while considering the costs associated with initial, maintenance, and energy cost for cooling purposes. As per the LCC analysis (Table 4.11), the conventional wall has less initial cost compared to the green wall which has a 19% cost saving. The reason for the high initial cost of the green wall is the additional cost of components due to the plants and support structure. In terms of the maintenance cost, the green wall shows less NPV compared to the conventional wall and thereby saves 29% of the cost. This saving mainly occurred due to the less external painting renovation frequency of green wall compared to the conventional wall due to green wall acting as a protecting layer to the building's external wall surface. When considering the overall NVP value, the conventional wall shows a 5% of LCC saving. However, when considering the energy cost saving of green walls, it can increase by 55% of cost saving for green walls compared to the conventional wall. Hence, it is clear that, though the initial cost of a green wall is greater than the conventional wall, by considering the energy-saving benefit of the green wall, a green wall can offset the negative effect of the high initial cost.

6.3 Conclusions of the Study

The study concludes that in global as well as in Sri Lanka, there are three main alternative types of green walls in practice; direct green facades, indirect green façades, and living walls. Having incorporated these green walls into the buildings benefits in terms of environmental, economical, and social aspects. However, the benefits may vary with the green wall type, country/climate, material used, plant species used, etc. Amongst the various benefits of green walls, energy-saving potential benefits of green walls are significant. The current study assessed the energy-saving potential of indirect green façade with limited to the selected case study profile and concluded that the conventional wall accounts for additional 101 W/m^2 per hour of heat transfer compared to the green wall, and thus green wall can save a minimum of 70% of energy cost for cooling purposes. This study further asses the LCC performance of a green wall compared to the conventional wall and showed that the initial cost of a green wall is 19% higher than the comparable conventional wall while the maintenance and potential energy cost for cooling purposes resulted in 29% and 65% savings to the green wall, respectively. Hence, the study findings facilitate that having green walls in the building would benefit in terms of every aspect.

6.4 Limitations of the Study

The current study based the assessment of energy and LCC performance of green walls using a single case study application of an indirect green façade compared to a conventional wall. As per the case profile, the study was limited to the indirect green façade type with timber support structure and *Thunbergia laurifolia* plant species. Further, the research findings were limited to the Af climatic condition due to the selected case profile was situated in the Af climatic condition.

Due to the time constraints, temperature measurements were taken over the months of May and July as it was recorded as the minimum temperature period in the local context. Hence, the energy saving calculated in the current study is the minimum value, this can increase with higher temperature behaviours.

Further, the results of the study may depend upon the building occupants and the electrical equipment that operated during the period of obtaining temperature measurements.

However, similar climatic conditions exist in a lot of South Asian and South East Asian countries. Hence this case study results can be contextualised and generalised into other similar contexts.

6.5 Recommendations

The recommendations to enhance green wall application in Sri Lanka are as below.

- **Consideration of the barriers towards the green wall application in Sri Lanka and propose strategies to overcome those barriers**
  The study identified a number of barriers towards green wall application with their root causes. These barriers need to be thoroughly considered when implementing green wall concept within the country.
- **Encouraging the investors on the concept of "economic benefit of green walls can offset the negative effect of high initial cost"**

  Most investors are reluctant to invest their money in green wall construction due to its high initial cost. However, when considering the economic benefits of green walls, it is clear that those economic benefits can offset the high initial cost of green walls. Encouraging the investors in this concept can increase the investments in green wall applications.

- **Conduct awareness programmes regarding green wall technology and the benefits of green walls**
  The importance of green wall technology and the benefits that can be obtained through green wall implementation should be convinced to the community through awareness programmes and thereby encourage the people to apply green walls to their properties
- **Encourage relevant authorities to allocate the funds and incentives for green wall application**
  It is recommended that the authorities should pay attention to providing funding and incentives to promote green wall applications within the country. For example, can allocate some funds for the building owners who hope to implement green walls in their premises as loans. In terms of incentives, authorities can release the buildings that have green walls from their taxes.

6.6 Contribution to the Knowledge and Practice

Unlike previous studies, the current study assessed the LCC performance of green walls including energy performance by comparing a real-life case study of an indirect green facade with an identical conventional wall in the Sri Lankan context. In the case of the energy-saving potential of green walls, the case study was conducted over 21 days intermittently over the period end of May to the beginning of July which has minimum temperature behaviour over the year. Accordingly, assessed the energy performance of green walls. So, any other situation in the Sri Lankan context which is like high-temperature periods will contribute to higher energy-saving performance. Thereby, building owners can implement green walls on their premises to obtain the long-term energy-saving benefits of green walls.

Added to that, most of the previous studies focused on the comparison of alternative green wall types, and less attention was paid to comparison with conventional walls. Through the LCC approach, the study has compared every component of LCC of green walls with similar components of the conventional wall. The current study findings revealed that in terms of total LCC green walls are more cost-effective than conventional walls and the high initial cost of green walls compared to the conventional wall can be offset through economic benefits and maintenance cost savings. This would enable to the enhancement of the application of green walls in the wider context in Sri Lanka as well as the global context.

6.7 Further Research Directions

The following research directions are recommended for further study.

- To assess the LCC of indirect green façade in comparison to the conventional wall with an alternative study period (Can extend the same case profile).
- To assess the LCC of other green wall types; direct green façade and living walls in comparison to identical conventional walls
- To assess the LCC among alternative green wall types.
- To assess the other benefits in comparison to alternative green wall types.

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APPENDICES

APPENDIX A - DISCOUNT RATE CALCULATION

Sri Lanka Inflation Rate and Lending Rate (Last 10 Years)

Year	Inflation Rate	Lending Rate
2021	7.01%	11.20%
2020	6.15%	11.60%
2019	3.53%	11.60%
2018	2.14%	10.50%
2017	7.70%	7.00%
2016	3.96%	7.80%
2015	3.77%	12.50%
2014	3.18%	13.30%
2013	6.91%	9.40%
2012	7.54%	10.20%
2011	6.72%	15.70%
2010	6.22%	18.90%
2009	3.47%	17.10%
Min	**2.14%**	**7.00%**
Average	**5.25%**	**10.51%**
Max	**7.70%**	**13.30%**

Source: (Central Bank Sri Lanka, 2021)

$$\boldsymbol{Discount\ Rate} = \left(\frac{\mathbf{1}+\boldsymbol{i}}{\mathbf{1}+\boldsymbol{r}} - \mathbf{1}\right) \times \mathbf{100}\%$$

$\boldsymbol{i}$ **= Interest rate**

$\boldsymbol{r}$ **= Inflation rate**

$$Discount\ Rate = \left(\frac{1+0.0700}{1+0.0214} - 1\right) \times 100\%$$

(Min)

$= \underline{\underline{4.76\%}}$

$$Discount\ Rate = \left(\frac{1+0.1051}{1+0.0525} - 1\right) \times 100\%$$

(Average)

$= \underline{\underline{4.99\%}}$

$$Discount\ Rate = \left(\frac{1+0.1330}{1+0.0770} - 1\right) \times 100\%$$

(Max)

$= \underline{\underline{5.20\%}}$

APPENDIX B – AVERAGE SURFACE TEMPERATURE

Conventional wall Building - Surface Temperature (^0C)																								
Day	Ground Floor								First Floor								Second Floor							
	North Wall		East Wall		West Wall		South Wall		North Wall		East Wall		West Wall		South Wall		North Wall		East Wall		West Wall		South Wall	
	O	I	O	I	O	I	O	I	O	I	O	I	O	I	O	I	O	I	O	I	O	I	O	I
01	30.9	29.9	31.3	30.0	31.5	30.1	31.3	30.3	31.0	29.9	31.5	30.1	31.6	30.1	31.1	30.1	40.7	39.7	39.4	38.4	42.5	41.6	39.0	38.0
02	31.1	30.0	31.0	30.0	31.3	30.1	31.0	29.9	31.2	30.0	31.2	30.0	31.2	30.1	31.1	30.1	39.4	38.4	39.2	38.2	39.7	38.6	39.0	38.0
03	31.1	30.0	31.0	30.0	31.2	30.1	31.1	30.1	31.2	30.0	31.3	30.1	31.3	30.2	31.1	30.2	40.5	39.5	39.2	38.6	42.3	41.7	38.6	37.9
04	31.2	29.7	31.0	29.2	30.7	29.5	30.8	29.7	30.3	28.8	31.0	28.9	30.6	29.3	31.3	30.1	35.1	33.8	34.9	33.6	34.1	32.8	33.6	32.3
05	30.4	29.4	31.0	29.7	31.2	30.0	31.3	30.3	30.7	29.7	31.2	29.9	31.4	30.9	31.2	30.1	33.5	32.6	33.8	32.8	33.8	32.8	33.4	32.4
06	30.7	29.5	31.0	30.0	31.3	29.9	31.2	30.0	31.0	29.9	31.2	30.0	31.4	30.3	31.2	30.2	33.5	32.5	33.3	32.6	33.5	32.8	33.0	32.3
07	30.0	28.9	30.6	29.7	30.4	29.9	31.2	30.1	30.6	29.4	30.6	29.6	30.4	29.8	30.4	29.3	32.9	31.7	32.9	31.7	33.0	32.0	32.7	31.8
08	29.6	28.5	29.5	28.7	30.3	29.4	29.7	28.8	29.7	28.6	29.6	28.3	30.3	29.4	29.6	28.5	32.3	31.2	32.2	31.2	32.6	31.6	32.1	31.1
09	30.0	28.8	30.0	29.0	30.6	29.5	29.9	28.8	29.8	28.6	30.0	29.2	30.6	29.6	30.0	28.9	33.0	31.7	33.0	31.8	33.1	31.9	32.8	31.6
10	30.9	29.7	31.0	29.2	30.7	29.5	30.8	29.7	30.0	28.8	31.0	28.9	30.6	29.3	31.3	30.1	35.1	33.8	34.7	33.6	33.9	32.8	33.4	32.3
11	30.5	29.4	30.5	29.0	30.4	29.8	29.9	28.9	30.0	28.9	30.4	29.1	30.5	29.7	29.9	28.9	32.9	31.6	33.0	31.7	33.2	31.9	32.9	31.6
12	30.1	28.9	30.1	28.9	30.3	29.4	30.1	29.2	30.0	28.8	30.1	28.9	30.4	29.7	30.0	29.2	32.1	31.2	32.3	31.4	32.1	31.2	32.1	31.2
13	30.1	28.9	30.2	29.2	30.4	29.8	30.0	28.9	30.2	29.0	30.2	29.3	30.5	29.8	30.0	28.9	32.7	31.7	32.7	31.9	32.8	32.0	32.5	31.7
14	30.3	29.1	30.2	29.3	30.2	29.8	29.9	28.8	30.2	29.0	30.3	29.2	30.3	29.8	29.9	28.8	32.7	31.7	32.6	31.9	32.7	32.0	32.4	31.7
15	30.0	28.9	30.5	29.9	30.3	30.1	30.0	28.9	30.9	29.8	31.3	30.2	31.3	30.4	29.9	28.8	30.8	29.7	31.4	30.2	31.4	30.5	29.9	28.8
16	30.4	29.2	30.7	29.0	31.3	30.0	30.8	30.1	30.4	29.3	30.9	29.6	31.4	30.2	30.9	29.9	30.5	29.3	30.8	30.0	31.4	30.8	30.9	30.1
17	30.4	29.4	30.7	28.2	31.3	30.1	30.9	30.2	30.5	29.5	31.0	29.7	31.4	30.1	30.8	30.1	30.3	29.3	31.0	30.3	31.3	30.5	30.8	30.1
18	30.1	29.0	30.6	28.9	30.6	29.4	30.6	29.4	30.3	29.2	30.2	28.3	30.5	29.2	31.3	30.0	30.2	29.2	30.2	29.3	30.5	29.8	31.4	30.5
19	30.4	29.9	30.7	30.2	31.3	30.7	31.2	30.7	30.5	29.9	30.9	30.4	31.4	30.9	31.0	30.5	30.6	30.1	31.0	30.5	31.4	30.8	31.0	30.5
20	29.5	28.3	30.3	29.1	30.3	29.0	30.2	29.0	29.5	28.2	30.5	29.2	30.3	29.1	30.2	28.9	29.7	28.4	30.4	29.1	30.3	29.0	28.1	26.8
21	29.4	28.3	29.7	28.6	30.0	29.0	29.5	28.4	29.7	28.6	29.6	28.5	30.2	29.2	29.4	28.4	29.4	28.4	29.4	28.3	30.2	29.1	29.5	28.4
Mean	**30.3**	**29.2**	**30.5**	**29.3**	**30.8**	**29.8**	**30.5**	**29.5**	**30.4**	**29.2**	**30.7**	**29.4**	**30.8**	**29.9**	**30.6**	**29.5**	**33.2**	**32.2**	**33.2**	**32.2**	**33.6**	**32.7**	**32.8**	**31.9**
Difference	**1.12**		**1.23**		**0.98**		**1.01**		**1.12**		**1.27**		**0.98**		**1.04**		**1.08**		**0.99**		**0.95**		**0.96**	

Green wall Building - Surface Temperature (^{0}C)																								
Day	**Ground Floor**								**First Floor**								**Second Floor**							
	North Wall		**East Wall**		**West Wall**		**South Wall**		**North Wall**		**East Wall**		**West Wall**		**South Wall**		**North Wall**		**East Wall**		**West Wall**		**South Wall**	
	O	I	O	I	O	I	O	I	O	I	O	I	O	I	O	I	O	I	O	I	O	I	O	I
01	29.0	28.8	29.1	28.8	30.7	29.1	31.0	30.6	29.0	28.9	29.3	28.9	30.0	29.6	31.0	30.6	37.7	37.3	37.9	37.6	39.0	38.6	38.2	37.9
02	29.1	28.8	29.2	28.8	30.5	29.9	31.0	30.6	29.0	28.8	29.2	28.9	29.9	29.5	31.0	30.6	36.9	36.6	37.7	37.4	38.2	37.9	38.2	37.9
03	28.9	28.7	29.0	28.7	29.8	29.1	31.1	30.6	28.6	28.4	28.9	28.6	29.3	28.8	31.1	30.6	37.8	37.5	37.4	37.1	39.0	38.6	38.6	38.2
04	29.0	28.9	29.2	29.0	30.1	29.7	30.8	30.5	28.9	28.7	29.1	29.0	29.9	29.8	31.1	30.8	37.0	36.8	37.7	37.5	39.3	39.1	34.1	33.8
05	29.1	29.0	29.1	28.9	30.5	30.2	30.3	29.9	28.9	28.8	29.1	28.9	29.9	29.7	30.1	29.7	33.1	33.0	33.6	33.5	33.0	32.8	33.1	33.0
06	29.6	29.3	29.6	29.3	30.3	30.0	30.9	30.4	29.5	29.3	29.6	29.3	30.2	30.0	30.9	30.4	37.0	36.8	37.7	37.5	39.3	39.1	34.0	33.8
07	28.7	28.5	29.0	28.8	28.8	28.5	30.8	30.2	28.7	28.5	28.9	28.6	29.2	28.6	30.9	30.3	37.8	37.5	31.9	31.7	32.3	32.0	32.0	31.8
08	28.9	28.7	29.1	28.9	30.0	29.8	30.4	29.9	28.8	28.7	29.0	28.7	29.4	29.1	30.4	29.9	34.7	34.5	35.0	34.8	35.7	35.5	35.5	35.3
09	29.0	28.8	29.1	29.0	30.5	30.2	30.5	30.2	29.3	29.2	29.3	29.1	29.9	29.8	30.5	30.2	36.7	36.6	37.5	37.4	38.0	37.9	38.0	37.9
10	29.0	28.8	29.2	29.0	30.0	29.7	30.6	30.3	29.0	28.8	29.1	29.0	29.9	29.7	30.5	30.2	37.0	36.8	37.7	37.5	39.3	39.1	34.0	33.8
11	28.9	28.7	29.1	29.0	30.3	30.1	30.6	30.2	29.0	28.8	28.9	28.8	29.9	29.7	30.9	30.5	37.4	37.3	37.8	37.6	38.7	38.6	34.0	33.8
12	28.5	28.4	28.9	28.6	28.9	28.8	30.0	29.7	28.9	28.8	29.2	29.0	29.7	29.5	30.0	29.7	37.0	36.9	38.3	38.2	38.1	37.9	34.9	34.8
13	28.8	28.7	29.0	28.9	29.9	29.6	30.3	30.0	28.7	28.6	29.0	28.8	29.3	29.1	30.0	29.7	37.7	37.5	34.7	34.6	39.0	38.9	37.4	37.2
14	28.4	28.3	28.6	28.6	28.9	28.8	30.5	29.9	28.5	28.4	28.8	28.6	29.0	28.9	30.5	29.9	37.9	37.8	37.4	37.2	40.9	40.8	37.0	36.9
15	28.1	27.7	28.5	28.1	29.1	28.7	28.5	28.1	28.6	27.5	29.0	26.9	29.2	27.9	28.7	26.9	28.7	27.7	28.9	27.6	29.2	28.4	28.9	27.6
16	29.5	29.0	29.2	28.7	30.7	30.1	30.8	30.3	29.3	29.0	29.3	28.9	30.0	29.7	30.8	29.9	29.4	28.9	29.3	29.0	30.1	29.7	30.7	30.4
17	29.0	28.6	29.2	28.8	29.8	29.0	30.9	30.2	28.7	28.4	29.0	28.6	29.3	28.8	30.8	29.6	28.8	28.4	29.0	28.6	29.3	28.8	30.9	30.5
18	28.9	28.7	29.2	29.0	30.1	29.6	30.7	29.6	29.2	28.7	29.2	29.0	29.9	29.7	31.0	30.1	29.1	28.7	29.3	28.6	29.8	29.2	30.9	30.2
19	29.2	28.9	29.1	28.9	30.4	30.2	30.1	29.9	29.2	28.8	29.1	28.9	29.9	30.0	30.1	30.0	29.2	28.9	29.1	28.8	29.8	29.7	30.0	29.9
20	28.8	28.7	29.0	28.9	29.7	29.6	30.8	30.7	28.7	28.4	28.8	28.6	29.1	28.7	30.8	30.7	28.8	28.5	28.9	28.7	29.1	28.7	30.7	30.6
21	29.1	28.9	29.2	29.1	30.1	29.9	30.4	30.2	29.0	28.8	29.3	29.1	29.6	29.4	30.3	30.2	29.1	29.0	29.0	28.9	29.6	29.4	30.3	30.1
Mean	28.9	28.7	29.1	28.8	29.9	29.6	30.5	30.1	28.9	28.7	29.1	28.8	29.7	29.3	30.5	30.0	34.2	34.0	34.1	33.8	35.1	34.8	33.9	33.6
Difference	**0.23**		**0.23**		**0.40**		**0.43**		**0.24**		**0.33**		**0.32**		**0.53**		**0.27**		**0.29**		**0.27**		**0.27**	

APPENDIX C – COST BREAKDOWN DETAILS

Cost Breakdown – Conventional wall Building

<u>Initial Cost</u>

Item No	Item Description	Unit	Qty	Rate	Amount
Ground Floor					
1	Block Work *6" thick cement sand Cellular block wall (blocks confirming to S.L.S.855 and subject to the approval of sample blocks) in cement and sand mortar 1:5 on the ground floor.*	m^2	77.88	2,714.75	211,424.50
2	Internal Plastering - *Plastering 5/8" thick to walls in cement and sand 1:5 finished smooth with two coats of skim coat.*	m^2	74.28	1,316.15	97,763.35
3	External Plastering - *Plastering 5/8" thick to walls in cement and sand 1:5 finished semi-rough*	m^2	77.88	841.77	65,556.68
4	Internal Painting - *Painting walls with two coats of emulsion paint including preparing the surface*	m^2	74.28	415.07	30,831.40
5	External Painting - *Painting walls with two coats of weather shield paint including preparing the surface.*	m^2	77.88	484.07	37,699.29
6	Door - *glazed and paneled 11/8" thick single sash hung on 33/4"x23/4" frame.*	m^2	9.90	21,767.48	215,498.05
7	Window - *glazed 1" sash and 33/4"x23/4 "frame.*	m^2	30.24	22,789.68	689,159.92
	Total initial cost for ground Floor				**1,347,933.20**
First Floor					
8	Block Work *6" thick cement sand Cellular block wall (blocks confirming to S.L.S.855 and subject to the approval of sample blocks) in cement and sand mortar 1:5 on the ground floor.*	m^2	77.88	2,986.22	232,566.95
9	Internal Plastering - *Plastering 5/8" thick to walls in cement and sand 1:5 finished smooth with two coats of skim coat.*	m^2	74.28	1,447.76	107,539.69

10	External Plastering - *Plastering 5/8" thick to walls in cement and sand 1:5 finished semi-rough*	m^2	77.88	925.94	72,112.35
11	Internal Painting - *Painting walls with two coats of emulsion paint including preparing the surface*	m^2	74.28	456.58	33,914.54
12	External Painting - *Painting walls with two coats of weather shield paint including preparing the surface.*	m^2	77.88	532.48	41,469.21
13	Door - *glazed and paneled 11/8" thick single sash hung on 33/4"x23/4" frame.*	m^2	9.90	23,944.23	237,047.86
14	Window - *glazed 1" sash and 33/4"x23/4 "frame.*	m^2	30.24	25,068.65	758,075.92
	Total initial cost for first Floor				**1,482,726.52**
	Second Floor				
15	Block Work *6" thick cement sand Cellular block wall (blocks confirming to S.L.S.855 and subject to the approval of sample blocks) in cement and sand mortar 1:5 on the ground floor.*	m^2	77.88	3,284.84	255,823.64
16	Internal Plastering - *Plastering 5/8" thick to walls in cement and sand 1:5 finished smooth with two coats of skim coat.*	m^2	74.28	1,592.54	118,293.66
17	External Plastering - *Plastering 5/8" thick to walls in cement and sand 1:5 finished semi-rough*	m^2	77.88	1,018.54	79,323.59
18	Internal Painting - *Painting walls with two coats of emulsion paint including preparing the surface*	m^2	74.28	502.23	37,305.99
19	External Painting - *Painting walls with two coats of weather shield paint including preparing the surface.*	m^2	77.88	585.72	45,616.14
20	Door - *glazed and paneled 11/8" thick single sash hung on 33/4"x23/4" frame.*	m^2	9.90	26,338.65	260,752.64
21	Window - *glazed 1" sash and 33/4"x23/4 "frame.*	m^2	30.24	27,575.51	833,883.51
	Total initial cost for second Floor				**1,630,999.17**
	Total initial cost for ground, first, and second Floor				**4,461,658.88**

Maintenance Cost

Item No	Item Description	Unit	Qty	Rate	Amount	Period
Ground Floor						
Redecoration						
1	Internal Painting	m^2	74.28	415.07	30,831.40	Every 2 years
2	External Painting	m^2	77.88	484.07	37,699.29	Every 2 years
Replacement						
3	Replacing Doors	m^2	9.90	21,767.48	215,498.05	Every 40 years
4	Replacing Windows	m^2	30.24	22,789.68	689,159.92	Every 40 years
5	Minor Repairs	item			20,000.00	Every 20 years
First Floor						
Redecoration						
6	Internal Painting	m^2	74.28	456.58	33,914.54	Every 2 years
7	External Painting	m^2	77.88	532.48	41,469.21	Every 2 years
Replacement						
8	Replacing Doors	m^2	9.90	23,944.23	237,047.86	Every 40 years
9	Replacing Windows	m^2	30.24	25,068.65	758,075.92	Every 40 years
10	Minor Repairs	item			20,000.00	Every 20 years
Second Floor						
Redecoration						
11	Internal Painting	m^2	74.28	502.23	37,305.99	Every 2 years
12	External Painting	m^2	77.88	585.72	45,616.14	Every 2 years
Replacement						
13	Replacing Doors	m^2	9.90	26,338.65	260,752.64	Every 40 years
14	Replacing Windows	m^2	30.24	27,575.51	833,883.51	Every 40 years
15	Minor Repairs	item			20,000.00	Every 20 years

Cost Breakdown – Green Wall Building

Block Wall

<u>Initial Cost</u>

Item No	Item Description	Unit	Qty	Rate	Amount
Ground Floor					
1	Block Work *6" thick cement sand Cellular block wall (blocks confirming to S.L.S.855 and subject to the approval of sample blocks) in cement and sand mortar 1:5 on the ground floor.*	m^2	63.96	2,714.75	173,635.22
2	Internal Plastering - *Plastering 5/8" thick to walls in cement and sand 1:5 finished smooth with two coats of skim coat.*	m^2	60.36	1,316.15	79,442.60
3	External Plastering - *Plastering 5/8" thick to walls in cement and sand 1:5 finished semi-rough*	m^2	63.96	841.77	53,839.31
4	Internal Painting - *Painting walls with two coats of emulsion paint including preparing the surface*	m^2	60.36	415.07	25,053.62
5	External Painting - *Painting walls with two coats of weather shield paint including preparing the surface.*	m^2	63.96	484.07	30,961.05
6	Door - *glazed and paneled 11/8" thick single sash hung on 33/4"x23/4" frame.*	m^2	9.90	21,767.48	215,498.05
7	Window - *glazed 1" sash and 33/4"x23/4 "frame.*	m^2	30.24	22,789.68	689,159.92
	Total initial cost for ground Floor				**1,267,589.77**
First Floor					
8	Block Work *6" thick cement sand Cellular block wall (blocks confirming to S.L.S.855 and subject to the approval of sample blocks) in cement and sand mortar 1:5 on the ground floor.*	m^2	63.96	2,986.22	190,998.74
9	Internal Plastering - *Plastering 5/8" thick to walls in cement and sand 1:5 finished smooth with two coats of skim coat.*	m^2	60.36	1,447.76	87,386.86

10	External Plastering - *Plastering 5/8" thick to walls in cement and sand 1:5 finished semi-rough*	m^2	63.96	925.94	59,223.24
11	Internal Painting - *Painting walls with two coats of emulsion paint including preparing the surface*	m^2	60.36	456.58	27,558.99
12	External Painting - *Painting walls with two coats of weather shield paint including preparing the surface.*	m^2	63.96	532.48	34,057.15
13	Door - *glazed and paneled 11/8" thick single sash hung on 33/4"x23/4" frame.*	m^2	9.90	23,944.23	237,047.86
14	Window - *glazed 1" sash and 33/4"x23/4 "frame.*	m^2	30.24	25,068.65	758,075.92
	Total initial cost for first Floor				**1,394,348.75**
					Second Floor
15	Block Work *6" thick cement sand Cellular block wall (blocks confirming to S.L.S.855 and subject to the approval of sample blocks) in cement and sand mortar 1:5 on the ground floor.*	m^2	63.96	3,284.84	210,098.62
16	Internal Plastering - *Plastering 5/8" thick to walls in cement and sand 1:5 finished smooth with two coats of skim coat.*	m^2	60.36	1,592.54	96,125.54
17	External Plastering - *Plastering 5/8" thick to walls in cement and sand 1:5 finished semi-rough*	m^2	63.96	1,018.54	65,145.57
18	Internal Painting - *Painting walls with two coats of emulsion paint including preparing the surface*	m^2	9.90	502.23	30,314.88
19	External Painting - *Painting walls with two coats of weather shield paint including preparing the surface.*	m^2	30.24	585.72	37,462.87
20	Door - *glazed and paneled 11/8" thick single sash hung on 33/4"x23/4" frame.*	m^2	63.96	26,338.65	260,752.64
21	Window - *glazed 1" sash and 33/4"x23/4 "frame.*	m^2	60.36	27,575.51	833,883.51
	Total initial cost for second Floor				**1,533,783.63**
	Total initial cost for ground, first, and second Floor				**4,195,722.15**

Maintenance Cost

Item No	Item Description	Unit	Qty	Rate	Amount	Period
Ground Floor						
Redecoration						
1	Internal Painting	m^2	60.36	415.07	25,053.62	Every 2 years
2	External Painting	m^2	63.96	484.07	30,961.05	Every 5 years
Replacement						
3	Replacing Doors	m^2	9.90	21,767.48	215,498.05	Every 40 years
4	Replacing Windows	m^2	30.24	22,789.68	689,159.92	Every 40 years
5	Minor Repairs	item			20,000.00	Every 20 years
First Floor						
Redecoration						
6	Internal Painting	m^2	60.36	456.58	27,558.99	Every 2 years
7	External Painting	m^2	63.96	532.48	34,057.15	Every 5 years
Replacement						
8	Replacing Doors	m^2	9.90	23,944.23	237,047.86	Every 40 years
9	Replacing Windows	m^2	30.24	25,068.65	758,075.92	Every 40 years
10	Minor Repairs	item			20,000.00	Every 20 years
Second Floor						
Redecoration						
11	Internal Painting	m^2	60.36	502.23	30,314.88	Every 2 years
12	External Painting	m^2	63.96	585.72	37,462.87	Every 5 years
Replacement						
13	Replacing Doors	m^2	9.90	26,338.65	260,752.64	Every 40 years
14	Replacing Windows	m^2	30.24	27,575.51	833,883.51	Every 40 years
15	Minor Repairs	item			20,000.00	Every 20 years

Indirect Green Façade

<u>Initial Cost</u>

No	Item Description	Unit	Qty	Rate	Amount
Care taking of plants					
1	Fertilizer (Compost and coir dust)	item		300.00	300.00
2	Unskilled Labour (for filling soil, planting works, watering, fertilization)	hrs	6	250.00	1,500.00
	Sub Total 1				***1,800.00***
Preparation of growing media					
3	Unskilled Labour (for digging pits, filling soil, planting works, watering, fertilization)	dys	1	2,000.00	2,000.00
	Sub Total 2				***2,000.00***
Preparation of Support structure					
4	Cinnamon Timber				29,976.00
5	Kubuk Timber				52,777.78
6	Labour (Fixing)				15,079.37
7	Tools and Equipment				7,539.68
8	Finishes with labour cost				30,580.00
	Sub Total 3				***135,952.83***
Installation					
4	Labour (Fixing)				30,158.73
5	Tools and Equipment				15,079.37
6	Transport to the site				11,309.52
	Sub Total 3				***56,547.62***
Total initial cost of indirect green wall					***196,300.45***

Maintenance Cost

No	Item Description	Unit	Qty	Rate	Amount	Time Period
Care taking of plants						
1	Fertilizer (Compost and coir dust)	item		300.00	300.00	Every month for first 3 month
2	Unskilled Labour (for filling soil, planting works, watering, fertilization)	hrs	6	250.00	1,500.00	
	Sub Total 1				***1,800.00***	
Pruning						
3	Unskilled Labour (for pruning)	days	1.5	2,000.00	3,000.00	Every 6 month after first year
	Sub Total 2				***3,000.00***	

APPENDIX D – CALCULATIONS FOR SENSITIVITY ANALYSIS

If lifetime = 30 years and DCF = 4.99%

LCC calculation of the conventional wall				
Time	**Description**	**Value (LKR)**	**Discount Rate 4.99%**	**PV (LKR)**
Initial cost				
0	Initial Cost	4,461,658.88	1	4,461,658.88
Total Initial cost (NPV)				**4,461,658.88**
Total Initial cost per m^2 (NPV)				**10,776.95**
Maintenance cost				
2nd, 4th, 6th, 8th, …………….26th,28th	Redecoration Cost (Internal and External)	226,836.56	7.27	1,649,670.80
40th	Replacement Cost	2,994,417.90	0.00	-
20th	Repairing Cost	60,000.00	0.38	22,640.14
Total Maintenance cost (NPV)				**1,672,310.95**
Total Maintenance cost per m^2 (NPV)				**4,039.40**
Total NPV				**6,133,969.83**
Total NPV per m^2				**14,816.35**
Energy cost				
1 - 30 years	Energy Cost	2,354,640.53	15.38	36,222,242.17
Total Energy cost (NPV)				**6,222,242.17**
Total Energy cost per m^2 (NPV)				**87,493.34**
Total NPV including energy cost				**42,356,212.00**
Total NPV per m^2				**102,309.69**

LCC calculation of the green wall				
Time	**Description**	**Value (LKR)**	**Discount Rate 4.99%**	**PV (LKR)**
Initial cost				
0	Block Wall	4,195,722.15	1	4,195,722.15
0	Green wall	196,300.45	1	196,300.45
Total Initial cost (NPV)				**4,392,022.60**
Total Initial cost per m^2 (NPV)				**12,842.17**
Maintenance cost				
2nd, 4th, 6th, 8th, …………26th,28th	Redecoration Cost (Internal)	82,927.49	7.27	603,090.90
5th, 10th, 15th, 20th, 25th	Redecoration Cost (External)	102,481.06	2.55	261,588.48
40th	Replacement Cost	2,994,417.90	0.00	-

20th	Repairing Cost	60,000.00	0.38	22,640.14
1/12th, 2/12th,3/12th	Care taking of Plants	1,800.00	2.98	5,356.35
1.5th, 2nd, 2.5th, 3rd, 3.5th,4th,4.5th,......... ....29th,29. 5th	Pruning	3,000.00	28.99	86,957.87
Total Maintenance cost (NPV)				**979,633.74**
Total Maintenance cost per m^2 (NPV)				**2,864.43**
Total NPV				**5,371,656.34**
NPV per m^2				**15,706.60**
Energy cost				
1st	Energy Cost	1,935,067.19	0.95	1,843,030.17
2 - 30Years	Energy Cost	585,576.57	15.15	8,872,395.10
Total Energy cost (NPV)				**10,715,425.27**
Total Energy cost per m^2 (NPV)				**31,331.65**
Total NPV including energy cost				**16,087,081.61**
NPV per m^2				**47,038.25**

If lifetime = 50 years and DCF = 4.99%

LCC calculation of the conventional wall				
Time	**Description**	**Value (LKR)**	**Discount Rate 4.99%**	**PV (LKR)**
Initial cost				
0	Initial Cost	4,461,658.88	1	4,461,658.88
Total Initial cost (NPV)				**4,461,658.88**
Total Initial cost per m^2 (NPV)				**10,776.95**
Maintenance cost				
2nd, 4th, 6th, 8th, …………….46th,48th	Redecoration Cost (Internal and External)	226,836.56	8.83	2,002,216.40
40th	Replacement Cost	2,994,417.90	0.14	426,351.94
20th, 40th	Repairing Cost	60,000.00	0.52	31,183.08
Total Maintenance cost (NPV)				**2,459,751.41**
Total Maintenance cost per m^2 (NPV)				**5,941.43**
Total NPV				**6,921,410.29**
Total NPV per m^2				**16,718.38**
Energy cost				
1 - 50 years	Energy Cost	2,354,640.53	18.27	43,027,433.65
Total Energy cost (NPV)				**43,027,433.65**
Total Energy cost per m^2 (NPV)				**103,931.00**

Total NPV including energy cost	**49,948,843.94**
Total NPV per m^2	**120,649.38**

LCC calculation of the green wall				
Time	**Description**	**Value (LKR)**	**Discount Rate 4.99%**	**PV (LKR)**
Initial cost				
0	Block Wall	4,195,722.15	1	4,195,722.15
0	Green wall	196,300.45	1	196,300.45
Total Initial cost (NPV)				**4,392,022.60**
Total Initial cost per m^2 (NPV)				**12,842.17**
Maintenance cost				
2nd, 4th, 6th, 8th, …………46th,48th	Redecoration Cost (Internal)	82,927.49	8.83	731,975.42
5th, 10th, 15th, 20th, 25th, 30th, 35th, 40th, 45th	Redecoration Cost (External)	102,481.06	2.97	303,959.75
40th	Replacement Cost	2,994,417.90	0.14	426,351.94
20th, 40th	Repairing Cost	60,000.00	0.52	31,183.08
1/12th, 2/12th,3/12th	Care taking of Plants	1,800.00	2.98	5,356.35
1.5th, 2nd, 2.5th, 3rd, 3.5th,4th,4.5th,......... ....49th,49.5th	Pruning	3,000.00	34.98	104,945.42
Total Maintenance cost (NPV)				**1,603,771.95**
Total Maintenance cost per m^2 (NPV)				**4,689.39**
Total NPV				**5,995,794.55**
NPV per m^2				**17,531.56**
Energy cost				
1st	Energy Cost	1,935,067.19	0.95	1,843,030.17
2 - 50Years	Energy Cost	585,576.57	18.19	10,649,295.27
Total Energy cost (NPV)				**2,492,325.44**
Total Energy cost per m^2 (NPV)				**36,527.27**
Total NPV including energy cost				**18,488,119.99**
NPV per m^2				**54,058.83**

If lifetime = 40 years and DCF = 4.76%

LCC calculation of the conventional wall				
Time	**Description**	**Value (LKR)**	**Discount Rate 4.76%**	**PV (LKR)**
Initial cost				
0	Initial Cost	4,461,658.88	1	4,461,658.88
Total Initial cost (NPV)				**4,461,658.88**
Total Initial cost per m^2 (NPV)				**10,776.95**
Maintenance cost				
2nd, 4th, 6th, 8th, ……………36th,38th	Redecoration Cost (Internal and External)	226,836.56	8.51	1,930,252.91
40th	Replacement Cost	2,994,417.90	0.00	-
20th	Repairing Cost	60,000.00	0.39	23,680.60
Total Maintenance cost (NPV)				**1,953,933.52**
Total Maintenance cost per m^2 (NPV)				**4,719.65**
Total NPV				**6,415,592.39**
Total NPV per m^2				**15,496.60**
Energy cost				
1 - 40 years	Energy Cost	2,354,640.53	17.74	41,777,757.61
Total Energy cost (NPV)				**1,777,757.61**
Total Energy cost per m^2 (NPV)				**100,912.46**
Total NPV including energy cost				**48,193,350.00**
Total NPV per m^2				**116,409.06**

LCC calculation of the green wall				
Time	**Description**	**Value (LKR)**	**Discount Rate 4.76%**	**PV (LKR)**
Initial cost				
0	Block Wall	4,195,722.15	1	4,195,722.15
0	Green wall	196,300.45	1	196,300.45
Total Initial cost (NPV)				**4,392,022.60**
Total Initial cost per m^2 (NPV)				**12,842.17**
Maintenance cost				
2nd, 4th, 6th, 8th, …………36th,38th	Redecoration Cost (Internal)	82,927.49	8.51	705,666.83
5th, 10th, 15th, 20th, 25th, 30th, 35th	Redecoration Cost (External)	102,481.06	3.07	314,695.51
40th	Replacement Cost	2,994,417.90	0.00	-
20th	Repairing Cost	60,000.00	0.39	23,680.60

1/12th, 2/12th,3/12th	Care taking of Plants	1,800.00	2.98	5,358.35
1.5th, 2nd, 2.5th, 3rd, 3.5th,4th,4.5th,......... ....39th,39.5th	Pruning	3,000.00	33.82	101,445.90
Total Maintenance cost (NPV)				**1,150,847.20**
Total Maintenance cost per m² (NPV)				**3,365.05**
			Total NPV	**5,542,869.80**
			NPV per m²	**16,207.22**
Energy cost				
1st	Energy Cost	1,935,067.19	0.95	1,847,175.35
2 - 40Years	Energy Cost	585,576.57	17.59	10,298,513.44
Total Energy cost (NPV)				**12,145,688.79**
Total Energy cost per m² (NPV)				**35,513.71**
			Total NPV including energy cost	**17,688,558.59**
			NPV per m²	**51,720.93**

If lifetime = 40 years and DCF = 5.20%

LCC calculation of the conventional wall				
Time	**Description**	**Value (LKR)**	**Discount Rate 4.76%**	**PV (LKR)**
Initial cost				
0	Initial Cost	4,461,658.88	1	4,461,658.88
Total Initial cost (NPV)				**4,461,658.88**
Total Initial cost per m² (NPV)				**10,776.95**
Maintenance cost				
2nd, 4th, 6th, 8th, ……………36th,38th	Redecoration Cost (Internal and External)	226,836.56	8.01	1,816,245.12
40th	Replacement Cost	2,994,417.90	0.00	-
20th	Repairing Cost	60,000.00	0.36	21,770.44
Total Maintenance cost (NPV)				**1,838,015.56**
Total Maintenance cost per m² (NPV)				**4,439.65**
			Total NPV	**6,299,674.43**
			Total NPV per m²	**15,216.60**
Energy cost				
1 - 40 years	Energy Cost	2,354,640.53	16.70	39,322,892.12
Total Energy cost (NPV)				**39,322,892.12**
Total Energy cost per m² (NPV)				**94,982.83**
			Total NPV including energy cost	**45,622,566.56**

Total NPV per m²	**110,199.44**

LCC calculation of the green wall				
Time	**Description**	**Value (LKR)**	**Discount Rate 4.76%**	**PV (LKR)**
Initial cost				
0	Block Wall	4,195,722.15	1	4,195,722.15
0	Green wall	196,300.45	1	196,300.45
Total Initial cost (NPV)				**4,392,022.60**
Total Initial cost per m² (NPV)				**12,842.17**
Maintenance cost				
2^{nd}, 4^{th}, 6^{th}, 8^{th}, …………36^{th},38^{th}	Redecoration Cost (Internal)	82,927.49	8.01	663,987.57
5^{th}, 10^{th}, 15^{th}, 20^{th}, 25^{th}, 30^{th}, 35^{th}	Redecoration Cost (External)	102,481.06	2.88	295,004.91
40^{th}	Replacement Cost	2,994,417.90	0.00	-
20^{th}	Repairing Cost	60,000.00	0.36	21,770.44
$1/12^{th}$, $2/12^{th}$,$3/12^{th}$	Care taking of Plants	1,800.00	2.97	5,354.60
1.5^{th}, 2^{nd}, 2.5^{th}, 3^{rd}, 3.5^{th},4^{th},4.5^{th},……… ………………39^{th},39.5^{th}	Pruning	3,000.00	31.77	95,315.42
Total Maintenance cost (NPV)				**1,081,432.93**
Total Maintenance cost per m² (NPV)				**3,162.08**
Total NPV				**5,473,455.53**
NPV per m²				**16,004.26**
Energy cost				
1^{st}	Energy Cost	1,935,067.19	0.95	1,839,423.97
2 - 40Years	Energy Cost	585,576.57	16.57	9,702,133.90
Total Energy cost (NPV)				**11,541,557.87**
Total Energy cost per m² (NPV)				**33,747.25**
Total NPV including energy cost				**17,015,013.40**
NPV per m²				**49,751.50**