

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

Himalshi Tharanga Rupasinghe

(178003P)

Thesis submitted in partial fulfilment of the requirements for the degree Doctor of  
Philosophy in Civil Engineering

Department of Civil Engineering

University of Moratuwa

Sri Lanka

June 2022

## **DECLARATION**

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Archt. H T Rupasinghe  
Department of Civil Engineering  
University of Moratuwa  
Sri Lanka

Date

The above candidate has carried out research for the PhD thesis under my supervision.

Prof. R U Halwatura  
Department of Civil Engineering  
University of Moratuwa  
Sri Lanka

Date

## ABSTRACT

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

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

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

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

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

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

## **ACKNOWLEDGEMENTS**

The author is immensely grateful to her research supervisor Prof. Rangika Halwatura of the Department of Civil Engineering for the invaluable guidance, support and encouragement given throughout the research.

The support given by Prof. Chintha Jayasinghe, Prof. Athula Kulathilaka and Prof. Saman Bandara (Heads, Department of Civil Engineering during the period of the research), and Dr. Nimal Wijayaratna, Dr. Ahani Ranathunga, Prof. Kumari Gamage & Prof. Ashoka Perera (Research Coordinators, Department of Civil Engineering during the period of the research) is gratefully acknowledged.

Author extends her sincere gratitude to Senate Research Committee of the University of Moratuwa for funding the experimental research work. Dr. Inoka Manthilake of Department of Electrical Engineering and the fellow research assistants at Pro-Green Laboratory, Department of Civil Engineering are acknowledged for the critical comments given to refine the work towards a successful outcome.

Sincere gratitude is extended to Ms. Rasindu, Ms. Nilusha, Ms. Shalini for the assistance given in conducting field studies. The technical officers Mrs. Rukma, Mrs. Priyantha and Mr. Naveen of the Department of Civil Engineering and all the supportive staff who helped in many ways to make this research a success owns a heartfelt gratitude as well.

With much gratitude the author forwards a thank you to Manula, her dearest parents and her brother without whose love, care and continuous support given this would not have been a reality.

Finally, the author wishes to thank all those who contributed for the successful completion of this research.

# TABLE OF CONTENTS

Declaration	i
Abstract	ii
Acknowledgements	iii
Table of contents	iv
List of figures	vii
List of tables	xii
List of appendices	xii
1. Introduction	1
1.1 General	1
1.2 Need of the study	3
1.3 Objectives	5
1.4 Methodology	6
1.5 Main findings	8
1.6 Arrangement of the thesis	10
2. Literature review	11
2.1 Introduction to the chapter	11
2.2 Global environmental crisis	11
2.3 Urban environmental issues	13
2.4 Energy in the context of global environmental crisis	18
2.5 Building envelop design for energy efficiency	22
2.6 The concept of vertical greenery	26
2.7 Vertical greening based research studies	30
2.8 Chapter summery	34

3. Public & designer perception on vertical greening	36
3.1 Introduction to the chapter	36
3.2 Vertical greenery in Sri Lankan context	36
3.3 Perception of general public on vertical greening	37
3.4 Occupant satisfaction on vertical greening	42
3.5 Designer perception on vertical greening	48
3.6 Discussion	55
3.7 Chapter summary	59
4. Identifying the local situation of vertical greening in Sri Lanka	61
4.1 Introduction to the chapter	61
4.2 Vertical greening applications in local context	61
4.3 On-site field investigation for thermal performance analysis	66
4.4 Performance evaluation of existing vertical greening	70
4.5 Findings of the field study stage for thermal performance analysis	71
4.6 Relative humidity and CO <sub>2</sub> measurements near existing vertical greenery	79
4.7 Internal air temperature moderation through VGS	81
4.8 Chapter summary	83
5. Plant species and growth media selection for the proposed modular panel vertical greening system	85
5.1 Introduction to the chapter	85
5.2 Selection of the plant species	85
5.3 Plant selection on-site investigation	89
5.4 Extended plant selection on-site investigation	95
5.5 Selection of growth media for the green panels	97
5.6 Chapter summary	102

6. Developing a green panel as a module of a sustainable external green skin in tropical context	103
6.1 Introduction to the chapter	103
6.2 Development of the modular panel	103
6.3 Development of the vertical green wall system	107
6.4 Thermal performance evaluation of the proposed vertical greening system	112
6.5 Chapter summery	113
7. Performance evaluation of vertical greening implementation in micro and macro contexts	115
7.1 Introduction to the chapter	115
7.2 Evaluating the benefits of the proposed VGS in building context	115
7.3 Evaluating the benefits of the proposed VGS application in urban context	122
7.4 Long term cost effectiveness of the proposed VGS	132
7.5 Chapter summery	146
8. Conclusion and recommendations	148
8.1 Conclusions	148
8.2 Recommendations	152
8.3 Further studies	153
Reference	154
Appendix A: Sample questionnaires	169
Appendix B: Sample building data collection sheet	181
Appendix C: Temperature readings of field investigations	182
Appendix D: Constant head permeability calculation tables	193
Appendix E: Field data collection sample for simulation studies	195

## LIST OF FIGURES

Figure 2.1: Urban green depletion in Colombo urban context from 2001-2015	17
Figure 2.2: Internal loads & external loads of buildings	21
Figure 2.3: Characterization of external double skin envelops	24
Figure 2.4: Benefit of integrating VGS as a double skin envelop	25
Figure 2.5: Vertical greening classification based on the construction method	28
Figure 2.6: Green façade typologies	29
Figure 2.7: Living wall typologies	29
Figure 2.8: Urban canyon temperature behavior with different green interventions	32
Figure 3.1: Procedure of the questionnaire survey analysis	37
Figure 3.2: Age & gender variation of sample	38
Figure 3.3: Personal observations and awareness on VGS	38
Figure 3.4: Level of agreement on VGS related benefits	39
Figure 3.5: Level of satisfaction gained by VGS	39
Figure 3.6: Preference of greened façade: before and after VGS integration	40
Figure 3.7: Experience of green integrated spaces	40
Figure 3.8: Reasons to prefer vertical greening	41
Figure 3.9: Reasons for not preferring vertical greening	41
Figure 3.10: Opinion on sustainability of vertical greening	42
Figure 3.11: Gender variation, age variation and occupant service time	43
Figure 3.12: Identified purpose of vertical greening	44
Figure 3.13: Occupant agreement on vertical greenery functions	45
Figure 3.14: Occupant opinion on comfort factors near to VGS	45
Figure 3.15: Perception on light penetration and heat reduction	46

Figure 3.16: Preference of vertical greening: before and after VGS integration	46
Figure 3.17: Occupant preference to have vertical greening at own residence	47
Figure 3.18: Reasons to like and dislike vertical greening	48
Figure 3.19: Gender variation, age variation and length of the practice	49
Figure 3.20: Design consideration for green applications	50
Figure 3.21: Application of VGS in design	51
Figure 3.22: Awareness on vertical greenery	51
Figure 3.23: Opinion on vertical greening benefits	52
Figure 3.24: Issues related to vertical greening	53
Figure 3.25: Preference on before and after VGS integration	54
Figure 3.26: Client demand for vertical greening	54
Figure 4.1: Procedure of field study stage 01	61
Figure 4.2: Direct green facades in Colombo context	62
Figure 4.3: Indirect green facades in Colombo context	63
Figure 4.4: Living walls in Colombo context	64
Figure 4.5: Planter boxes commonly used in LWS	65
Figure 4.6: Procedure of field investigation for thermal performance analysis	66
Figure 4.7: Temperature measuring points	70
Figure 4.8: Temperature reading of living walls – 1m from the surface	72
Figure 4.9: Temperature readings of living walls – 10cm from the surface	72
Figure 4.10: Temperature readings of living walls– Outer wall surface	73
Figure 4.11: Temperature readings of direct green facades– 1m from the surface	74
Figure 4.12: Temperature readings of direct green facades– 10cm from surface	74
Figure 4.13: Temperature readings of direct green facades– Outer wall surface	75
Figure 4.14: Temperature readings of indirect green facades– 1m from the surface	76

Figure 4.15: Temperature readings of indirect green facades– 10cm from the surface	76
Figure 4.16: Temperature readings of indirect green facades– Outer wall surface	77
Figure 4.17: RH variation near existing VGS types	80
Figure 4.18: Carbon dioxide profiles for green wall types	81
Figure 4.19: Selected case studies for further on-site investigation (A- Living wall, B- Direct green façade, C- Indirect green façade)	82
Figure 4.20: Results of the thermal performance on-site investigation of the existing vertical greening systems	83
Figure 5.1: Creating the modular panel samples	87
Figure 5.2: Experimented twelve plant species	88
Figure 5.3: Plant survival percentage during the trial period	90
Figure 5.4: Plant height increment over the observed time period	91
Figure 5.5: Selected five plant species for thermal behaviour observation	92
Figure 5.6: Recorded temperature at 20 cm in front of the panels at 1300h	93
Figure 5.7: Recorded substrate temperature of the panels at 1300h	93
Figure 5.8: On-site investigation of selected two plant species	95
Figure 5.9: Results of the thermal performance on-site investigation of the prototype green panels	96
Figure 5.10: Measuring the wet weight and dry weight of the samples	97
Figure 5.11: Compaction graph of the tested growth media samples	99
Figure 5.12: Conducting the permeability test for the growth media mix samples	99
Figure 5.13: The graph of $\Delta h$ and rate of flow for sample coir: sand 1:1	100
Figure 5.14: Permeability of the five mix samples	101
Figure 6.1: Designed modular panel for the proposed vertical greening system	104
Figure 6.2: Details of the proposed panel	104

Figure 6.3: Making of the actual modular panel	105
Figure 6.4: Development of the vegetated panels	105
Figure 6.5: Thermal performance analysis of the panels	106
Figure 6.6: Temperature measurement points	106
Figure 6.7: Results of the thermal performance analysis of the individual panels	107
Figure 6.8: Proposed modular panel green wall system	108
Figure 6.9: Setting up the modular panel green wall system	108
Figure 6.10: Field tests conducted for permeant wilting point investigation	109
Figure 6.11: Measuring the water requirement of a single panel	111
Figure 6.12: Experimental setup of the vertical modular panel green wall system	112
Figure 6.13: Thermal performance of the proposed green wall system	113
Figure 7.1: Pilot study in building scale	116
Figure 7.2: Results of the pilot study in building scale	117
Figure 7.3: Simulated office building for thermal regulation with vertical greening	118
Figure 7.4: Indoor air temperature behaviour of the simulated office space	119
Figure 7.5: Modeled building for energy consumption simulation	120
Figure 7.6: Energy consumption with blind brick wall as EDSE	121
Figure 7.7: Energy consumption with proposed VGS as EDSE	121
Figure 7.8: Comparison of internal air temperature with EDSE interventions	122
Figure 7.9: Pilot study in evaluating the thermal benefit in urban context	123
Figure 7.10: Selected buildings in different urban contexts for simulation study	125
Figure 7.11: Models simulated in Envi-met with and without vertical greenery	125
Figure 7.12: Urban air temperature behavior in selected urban contexts after VGS integration	127

Figure 7.13: Temperature contour map of Sethsiripaya urban context before and after VGS application	128
Figure 7.14: Temperature contour map of Matara MC urban context before and after VGS application	128
Figure 7.15: Temperature contour map of Kandy MC urban context before and after VGS application	129
Figure 7.16: Simulated urban context with and without vertical greenery	129
Figure 7.17: Temperature contour map of the urban context with and without vertical greenery	130
Figure 7.18: Urban air temperature behavior in macro urban contexts (with and without vertical greenery)	131
Figure 7.19: LCCA framework for VGS	136
Figure 7.20: Case study for the cost benefit analysis of proposed VGS	140
Figure 7.21: Comparison of costs and savings of the proposed VGS for 50 years	144

## **LIST OF TABLES**

Table 4.1: Category 01 - Living walls	67
Table 4.2: Category 02 - Indirect green facades	68
Table 4.3: Category 03 - Direct green facades	69
Table 5.1: Wet weight and dry weight of the tested samples	98
Table 5.2: Calculated moisture content and dry density of the tested samples	98
Table 5.3: Collected data and calculated rate of flow of coir: sand 1:1 sample	100
Table 5.4: Permeability of the five mix samples	101
Table 6.1: Measured wet and dry weight for permanent wilting point test	110
Table 7.1: Comparison of energy consumption with EDSE interventions	121
Table 7.2: Costs related to the VGS	141
Table 7.3: Total costs related to the VGS	143
Table 7.4: Saving potential for 50 years	144
Table 7.5: Total saving for 50 years	144

## **LIST OF APPENDICES**

Appendix A: Sample questionnaires	169
Appendix B: Sample building data collection sheet	181
Appendix C: Temperature readings of field investigations	182
Appendix D: Constant head permeability calculation tables	193
Appendix G: Field data collection sample for simulation studies	195