Journal of Building Design and Environment

Vol 3 Issue 3
DOI: 10.70401/jbde.2024.0004

Open Access Research Article

Benchmarking green technologies: a survey of non-domestic buildings in Sri Lanka

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Received: July 17, 2024 **Accepted:** October 08, 2024 **Published:** October 29, 2024

Cite this article: Sachchithananthan M, Ramachandra T, Thayananth M, Rotimi JOB. Benchmarking green technologies: a survey of non-domestic buildings in Sri Lanka. J Build Des Environ. 2024;3:37946. https://doi.org/10.70401/jbde.2024.0004

Abstract

The escalating demand for energy and resources in the construction industry, together with poor energy performance of existing buildings, pose challenges for sustainability. Despite the incorporation of advanced technologies in modern construction to reduce energy consumption, a significant number of buildings are yet to adopt sustainable practices, owing to lack of awareness about potential technologies, and the considerations for selection. To this end, the current study aims to survey commercial buildings to explore the technologies implemented together with the basis that influenced the implementation. A detailed survey including semi-structured interviews with professionals engaged in the selected non-domestic buildings were conducted. The selected buildings comprise three (3) certified retrofit, eight (8) certified new and seven (7) non-certified green. The findings show that the buildings have incorporated 54 different technologies under the main sustainability criteria of water efficiency, lighting, heating, ventilation, and air conditioning (HVAC) systems, indoor environmental quality, and sustainable site. Advanced technologies, such as free cooling appliances, on-site wastewater treatments, and water-efficient climate-tolerant plantings, were predominantly found in green-certified buildings, while non-certified buildings tend to adopt more universally applicable and accessible technologies, like LED lighting, compact fluorescent lamps, and low-flow plumbing fixtures. The paper presents a detailed analysis on use of technologies with different building function, green rating levels, and challenges faced. Hence, the study findings would facilitate technology adaptation for a given context by providing insights into the availability and adaptability of green retrofit technologies in the Sri Lankan context for non-domestic buildings.

Keywords: Green technologies, retrofit technologies, green certification, challenges, Sri Lanka

1. Introduction

The construction of new green buildings by demolishing existing structures often conflicts with energy conservation principles[1]. While an increasing number of buildings are being converted into green buildings, most existing structures were not originally designed in a sustainable manner[2]. Retrofitting these buildings with green technologies has emerged as a more efficient and sustainable alternative to new construction, providing significant opportunities to improve energy performance and reduce environmental impact[3].

Unfortunately, retrofitting existing buildings poses greater challenges than constructing new green buildings. For example, in existing multi-tenant commercial buildings, any sustainable retrofit or technology upgrade requires the cooperation and participation of a wide range of stakeholders[4,5]. Additionally, long payback periods, high upfront costs, and limited access to capital make green retrofits less attractive to investors and building owners[6-8]. Moreover, there is lack of retrofit experience and lack of understanding of the available retrofit technologies, which, combined with unwillingness of building owners to pay for retrofit prevent owners from undertaking sustainable retrofits[6-10].

Despite the growing availability of green technologies for retrofitting, the selection process remains complex[11]. Investors often underestimate the long-term benefits of retrofitting, particularly during the operational phase of the building[1-12]. This has prompted the need to evaluate the long-term performance, cost implications, and potential savings of retrofit technologies[8-13]. For example, Ma *et al*.[14] proposed various retrofit actions and decision support tools to upgrade building performance. Similarly, more efficient methods for selecting the best retrofit alternatives for existing buildings have been outlined in the study by Jagarajan *et al*.[15]. Alanne[16] proposed a multi- criteria 'knapsack' model to help designers select the most feasible retrofitting actions during the conceptual phase of retrofit projects. In addition, Lavy *et al*.[17] proposed a decision support model for semi-automated selection of retrofitting alternatives. Subsequently, Ma *et al*.[13] provided an orderly way to deal with appropriate determination and identification of the best retrofit alternatives for existing buildings.

Although, various decision making models have been developed to facilitate the selection of green retrofit technologies, practical implementation fall short of expectations. For instance, Mejjaouli & Alzahrani[18] developed a model using mixed integer linear programming (MILP) to select optimal energy retrofitting strategies for residential buildings, but its application to non-domestic buildings in Sri Lanka is limited due to differing building uses and energy consumption patterns. Also, Lu *et al*.[19] developed a framework which integrates energy simulation with cost-benefit analysis, yet excluded key retrofit technologies such as heating, ventilation, and air conditioning (HVAC) systems and renewable energy installations. Chen *et al*.[8] developed an agent-based homeowner decision-making model, which did not fully account for the heterogeneity and specificity of individual projects. Similarly, Shen[20] proposed the SimBldPy model, which uses advanced technologies like EnergyPlus, but its application is constrained by the high technical expertise and computing resources required.

In the context of Sri Lanka, its substantial existing buildings presents greater potential to reduce energy, waste, air pollution and global warming. However, only a limited number of buildings have been recognized as green certified for incorporating green features. This is largely due to the perception among investors in green buildings that such constructions are expensive[12]. Since the commencement of the retrofit trend in 2021, in Sri Lanka, only 11 (9%) buildings, 10 non-domestic and one single domestic building in the entire country, have achieved green certification[21].

The approach to the rating of green building varies from country to country due to difference in climatic conditions, cultures and traditions, building styles, and disparate environmental, economic, and social concerns. Non-domestic buildings vary in their operating characteristics, which can either create opportunities or impose limitations when selecting the most suitable green technologies to adopt in particular buildings[22]. In non-domestic buildings, sustainable retrofits or technology upgrades require the collaboration and engagement of various stakeholders, which could present numerous challenges[4]. As a result, industry professionals are reluctant to embrace green retrofit initiatives. To overcome these obstacles, comprehensive strategies are required to address financial, technical, and information barriers, and to foster a favorable environment for the widespread adoption of sustainable retrofit practices in non-domestic buildings[23].

Appropriate selection of retrofit technologies is essential for effective decision-making in green retrofit development[24]. Thus, a comprehensive guide for selecting retrofit technologies and overcoming these obstacles becomes imperative for the Sri Lankan context. Therefore, this research aims to explore the green technologies implemented towards facilitating green technology selection decision-making. The study will consider the challenges and applicability of green retrofit technologies in non-domestic buildings in Sri Lanka.

2. Literature Review

2.1 Green retrofit technologies

Green technology refers to advancements in the utilization of equipment, methods, and products to conserve the natural environment and resources, while minimizing and reducing their negative impact on human activities[25]. These technologies could enhance the sustainability of existing buildings by improving energy efficiency and indoor air quality with the use of renewable energy sources[26]. Thus the provision of fresh and filtered air throughout the building's interior, thereby elevating the overall performance of building structures[24-27]. Iravani *et al*.[25] and Zhang *et al*.[28] suggest that green retrofit technologies are desired to reduce environmental deterioration, greenhouse gas emissions, and conserve natural resources and energy. They increase the use of renewable energies, and promote a healthy and enhanced environment for all kinds of life.

Numerous green technologies have been developed to attain sustainability in the building sector[29,30]. However, the approach to green retrofit technology selection varies from country to country due to their inherent distinctiveness in terms of climatic conditions, cultures and traditions, various building styles, and disparate environmental, economic, and social concerns[11,22]. There are many categorisations of green technologies for sustainable development[25]. Through a comprehensive review of past studies, green retrofit technologies are grouped under the following seven major categories[26,31-33].

- Water efficiency technologies
- Lighting Technologies
- HVAC systems and Control Technologies
- Indoor environmental quality (IEQ) Technologies
- Building Envelope Technologies
- Indoor Environmental Quality Technologies
- Sustainable sites Technologies

Further details on each of the categories is provided in Section 4.

2.2 Green retrofit challenges

This section provides a review of green retrofit challenges in spite of its importance in the conservation of resources and energy[34,35]. Jagarajan *et al*.[15] concluded that green retrofitting is yet to reach its full potential in many countries because of some challenges engthy payback periods[11,36,37], high investment outlay requirements, and limited access to capital[38]. Furthermore, application of green retrofit technologies is hindered by the general lack of retrofits experience[36,37], and the understanding of available retrofit technologies. In the context of Sri Lanka, Ramachandra and Weerasinghe[1], report on very low uptake (1.5-

2.0%) by LEED certified green buildings. Table 1 presents the different types of challenges experienced in retrofitting buildings in different contexts.

Table 1. Green retrofits challenges.

Challenges	Sources
1) Market Challenges	
• Inadequate understanding and awareness of green retrofit • Scarcity of performance data for retrofitted existing structures • Lack of market consensus on leading green standards • Possibility of failing to meet market expectations	[10,15,25,38]
2) Political Challenges	
• Deficiency of monetary incentives • Tax and regulatory incentives are not consistent • Incentives with unknown expiry dates • Insufficient government and private sector investment and engagement	[8,10,11,20]
3) Financial Challenges	
• High initial capital cost • Transportation cost • Inadequate funds • Inadequate understanding of lifecycle costs	[1,8,21,25,28,39]
4) Green technological Challenges	
• Unreliable or unproven technology • Insufficient supply of green materials and technologies • The performance of new materials is not evaluated throughout time	[7,15,40]
5) Performance Challenges	

• Various considerations throughout the decision- making process for introducing green technology • Lack knowledge and training • Lack of professionally trained design teams	[5,15,21,24]

The **Table 1** reveals the common obstacles. For developed countries, the primary focus is on optimizing the implementation of existing green technologies and addressing market resistance[10,38]. This contrasts developing nations, where the challenges are more fundamental, and include financial limitations, and insufficient infrastructure to support the widespread adoption of green retrofitting practices[8,10,11]. Others include inconsistent policies, and market uncertainty that could affect the adoption of retrofit technologies in both contexts[8,20]. Although it has been suggested that the barriers to green retrofitting are global[15], their impact is felt differently in developed and developing countries. Therefore, a country based assessment is needed for accurate evaluation of green retrofitting solutions[8].

3. Research Methods

This study utilizes a qualitative approach to assess the influence of certain factors on the selection of green retrofit technologies. Thus, a survey was administered among newly constructed green and non-green certified non-domestic buildings. Professionals involved in the aforementioned building projects participated in the survey. For non-domestic green retrofit buildings, the focus was primarily on structures certified by GREENSL (GBCSL) due to limited data availability on buildings certified by LEED (Leadership in Energy and Environmental Design, in Sri Lanka[35]. Thus, the GREENSL grading system, developed by the Green Building Council of Sri Lanka (GBCSL) is common. This is modeled after LEED and promotes the design and construction of green buildings with a focus on cost-efficiency, health, and safety[41,42]. The analysis is based on GREENSL-certified buildings, while for newly certified non-domestic category of buildings, both GBSL and LEED certified buildings were examined.

3.1 Profile of the selected buildings

18 non-domestic buildings integrated with green technologies were selected through a survey. The buildings are categorized into three: (1) green certified retrofit buildings (GRB), (2) green certified new buildings (GNB) and (3) non-green certified buildings (NGB). Under these three categories, building with different functions, and green ratings were examined for variations in the technologies integrated in them.

To achieve a rational basis for comparison between the three main categories of buildings, an equal sample of buildings was intended to be surveyed for each category. However, information was obtained from only three (3) GRBs, eight (8) GNBs and seven (7) NGBs for the analysis. The profile of the surveyed buildings was summarized in **Table 2**.

Table 2. Profile of the surveyed buildings.

	Categories	GRBs (03)	GNBs (08)	NGBs (07)	Total
Type of Function	Office	02	07	03	**12**
	Institutional	01	-	02	**03**

	Hotel	-	01	02	**03**
Awarded Rating	Silver	01	-	-	**01**
	Gold	02	05	-	**07**
	Platinum	-	03	-	**03**
	Non-certified	-	-	07	**07**
Gross Floor Area (m2)	1,000-5,000	02	05	04	**11**
	5,000-10,000		02	03	**05**
	10,000-70,000	01	01	-	**02**
No of	Less than 4	00	05	03	**08**
storey	4 - 6	02	01	04	**07**
	Above 6	01	02	00	**03**
Building age	Less than 5yrs	-	02	01	**03**
	5 - 10yrs	01	04	04	**09**
	Above 10 yrs	02	02	02	**06**

GRB: green certified retrofit buildings; GNB: green certified new buildings; NGB: non-green certified buildings.

As indicated in **Table 2**, the surveyed buildings exhibit diverse characteristics across three selected building types. In terms of functions, most of the buildings are green certified offices. Further most of the certified buildings were Gold rated. Building sizes range widely, with a significant portion falling within 1,000-5,000 m^2 of gross floor area range. The majority of buildings are below 6-storeys, with varying ages distributed across different categories. This profile is further analyzed with the technologies implemented in the following section.

To collate the challenges and criteria involved in the selection of green retrofit technologies in the selected buildings, the study conducted interviews with professionals. One professional per building was interviewed. Those professionals included project manager (PNGB1), Engineers (PGNB1/PGNB4/ PNGB1/PNGB2/ PNGB4), Quantity Surveyor (PGNB8/ PNGB7), Facilities Manager (PGRB1/PGNB2/PGNB3/PGNB6/ PGNB7/PNGB6), Architect (PGRB3/PGNB5) and General Manager (PGRB2) with major of them having 05-15 years of experience in the field. Most of them (14 out of 18) have involved in green building projects as well. Regarding field experience, a significant portion (33%) has 10-15 years of experience, while 28% have 5-10 years. Majority of the participants (78%) have been involved in green projects, indicating a substantial level of experience and engagement within sustainable construction practices.

4. Findings and Discussion

4.1 Green technologies incorporated in the surveyed buildings and the selection basis

The survey for the study, was guided by a list of 42 retrofit technologies obtained from literature. Those retrofit technologies aim at achieving sustainability in buildings through various aspects such as water efficiency, lighting, HVAC systems, building envelope, indoor environmental quality and sustainable sites. Accordingly, the technologies in surveyed buildings are grouped under the above sustainability aspects in **Table 3**. According to the table, the surveyed buildings have integrated altogether 54 different technologies, twelve over those identified in literature, and marked under their respective categories.

Table 3. Retrofit technologies incorporated in the surveyed buildings.

Technologies	GRB			GNB								NGB							Total	Source
	GRB1	GRB2	GRB3	GNB1	GNB2	GNB3	GNB4	GNB5	GNB6	GNB7	GNB8	NGB1	NGB2	NGB3	NGB4	NGB5	NGB6	NGB7		
Water Efficiency Technologies																				
1)Low-flow plumbing faucets	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	18	[43,44]
2) Low flow shower, water closet, Urinals, and wash basin.	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	18	[44-49]
3)Dual flushing toilets*	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	18	Author
4)Less capacity cistern tank*	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	18	Author
5) Micro irrigation	√	√	√	-	√	√	-	√	√	√	√	-	-	√	-	-	-	-	12	[32]
6) Rainwater harvesting	√	√	√	√	√	√	√	-	√	-	√	-	-	√	-	-	-	-	10	[32,47,48]
7)Water efficient, climate tolerant plantings	-	√	-	-	√	√	-	√	√	√	√	-	-	-	-	-	-	-	07	[32,49,50]
8)High-efficiency automatic water control systems	√	√	-	√	-	-	√	-	√	-	√	-	-	-	-	-	-	-	06	[32]
9)On-site wastewater/greywater treatments	√	-	√	-	-	√	√	-	-	√	√	-	-	-	-	-	-	-	06	[47,49]
10)Rain sensors*	-	-	-	-	-	-	√	-	-	-	√	-	-	-	-	-	-	-	02	Author

11)Permeable surface technology	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	00	[32]
Lighting Technologies																				
1) LED lighting	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	18	[51]
2)Task Lighting	√	√	√	√	√	√	√	√	√	√	-	√	√	-	-	-	√	√	14	[52,53]
3)Daylight Linked Lighting Control System	√	√	√	√	√	√	√	√	√	√	-	-	-	-	-	-	-	-	11	[54]
4)Compact fluorescent lamps*	√	-	√	-	√	√	√	-	-	-	-	√	√	√	√	-	√	-	10	Author
5)Occupancy-based Lighting Control System	-	-	-	√	√	√	√	-	-	-	√	-	-	-	-	-	-	-	05	[52]
6)Light pipe technology	-	-	-	-	-	√	√	-	-	-	-	-	-	-	-	-	-	-	02	
7)Lighting Controlled by Time Scheduling	-	-	-	-	-	-	-	-	-	-	√	-	-	-	-	-	-	-	10	[54,56,57]
HVAC Systems and Controls Technologies																				
1)Optimum Start/Stop Controller	√	√	√	√	√	√	√	√	√	√	-	-	√	√	√	√	-	√	15	[58]
2)Free Cooling Applications	√	√	-	-	√	-	-	-	√	√	-	√	-	-	-	-	-	-	06	[59,60]
3) Load shedding and scheduling process*	√	-	-	√	√	-	-	√	-	-	√	-	-	-	-	-	-	-	05	Author
4)Demand Control Ventilation	-	-	-	-	√	√	√	-	√	-	-	-	-	-	-	-	-	-	04	[61]
5)Variable Refrigerant Volume (VRV) System*	-	-	√	-	-	-	-	-	-	-	√	-	-	-	-	-	-	-	02	Author
6)Variable Air Volume (VAV) System*	-	-	-	√	-	-	-	-	-	-	-	-	√	-	-	-	-	-	02	Author

7)Energy efficient chillers*	√	-	-	-	-	-	√	-	-	-	-	-	-	-	-	-	-	-	02	Author
8) Having motorizes louvers for heat*	-	-	-	-	-	-	-	√	-	-	-	-	-	-	-	-	-	-	01	Author
9) Rotary Heat wheels and Heat Pipes	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	00	[62]
10) Energy Recovery Ventilator (ERV)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	00	[59,61]
Building Envelope Technologies																				
1) Low emissivity glass doors/windows	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	18	[33]
2) Window shutters	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	18	[33,63]
3) Window shade	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	18	[33,63]
4) Low conductive frame doors/windows	√	√	√	√	√	-	√	√	√	√	√	√	√	√	-	-	-	-	18	[33]
5) Solar photovoltaic system	√	√	√	√	√	√	√	√	√	√	√	√	-	√	-	-	-	-	13	[26,33]
6) Cool roofs	√	-	√	√	√	√	√	√	√	√	-	-	-	-	-	-	-	-	09	[33,64]
7) Solar shading elements in the wall	√	√	√	√	√	√	√	-	√	√	-	-	-	-	-	-	-	-	09	[33,65]
8) Reflective surface roofs	√	-	√	-	√	√	√	√	√	-	-	-	-	√	-	-	-	-	08	[43,66]
9) Green roofs	-	√	-	-	√	√	√	-	-	-	√	-	-	-	-	-	-	-	05	[33,67]
10) Green wall	√	√	-	-	-	-	√	-	-	-	-	-	-	-	-	-	-	-	03	[33,48]
11) Opaque ventilated facades*	-	-	-	-	-	-	√	-	-	-	√	-	-	-	-	-	-	-	02	Author
12) Nano insulation	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	00	[33]

IEQ Technologies																				
1) Light-coloured paints	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	18	[31]
2) Ample ventilation for pollutant & thermal control	√	√	√	√	√	-	√	√	√	√	√	√	√	-	-	-	√	-	13	[31,47]
3) Cross ventilation	√	√	√	√	√	√	√	√	√	√	-	√	-	√	-	-	-	√	13	[68]
4) Co2 sensors	√	-	√	-	√	√	√	-	√	-	√	-	√	√	√	-	-	-	10	[1,69]
5) Negative-pressure smoking rooms	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	00	[70]
6) Wing Walls	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	00	[47]
7) Air filtration	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	00	[1,37]
8) Air sealing technique	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	00	[1]
Sustainable Sites Technologies																				
1) Roof top gardening	-	√	-	√	√	√	√	-	-	-	√	-	-	-	-	-	-	-	06	[31]
2) Vertical gardening	-	-	-	-	-	√	√	-	-	-	√	-	-	-	-	-	-	-	04	[31]
3) Cool pavement	√	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	01	[71]
4) Bicycle tracks	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	00	[1,31]
Other Technologies																				
1) Regular audit*	√	-	√	√	√	√	√	√	√	√	√	-	√	√	√	-	-	-	13	Author
2) Smart meters*	√	-	√	-	-	-	√	-	√	√	√	-	-	√	-	-	-	-	07	Author

GRB: green certified retrofit buildings; GNB: green certified new buildings; NGB: non-green certified buildings; IEQ: indoor environmental quality.

4.1.1 Water efficiency technologies

Along with literature, the survey identified 10 different technologies used in buildings to achieve water efficiency. Technologies like low-flow plumbing faucets, low flow shower, water closet, urinals, and wash basin, dual flushing toilets and less capacity cistern tank were available in all the surveyed buildings. The widespread implementation of these technologies in both green-certified buildings (GBs) and non-green buildings (NGBs) underscores their universal applicability. Hence, buildings that are prioritizing sustainability, can readily adopt these technologies, irrespective of green certification, due to their practicability and adaptability to diverse architectural contexts.

Notably, on-site wastewater/greywater treatments, water efficient, climate tolerant plantings, high-efficiency automatic water control systems and rain sensors were predominantly found in green-certified buildings (GBs). These findings indicate a close link between green certification and the adoption of these specific technologies. While, these four technologies are exclusively prevalent in GBs, none of the NGBs (7 out of 18 surveyed) implemented them.

Micro-irrigation and rainwater harvesting systems were incorporated into all three GRBs and the majority of NGBs (5 out of 7), highlighting their significance in obtaining green certification. Two (out of 3) retrofit buildings (GRBs) had high-efficiency automatic water control systems and on-site wastewater/greywater treatments, and four new green buildings (GNBs) were integrated with these technologies. This discrepancy highlights a potential gap in the adoption of advanced water control measures in GBs including new as well as retrofit buildings compared to non-certified buildings.

A similar challenge was observed in the adoption of water-efficient, climate-tolerant plantings, where only one retrofit building was implemented with this technology whereas most of the (six out of 7) new green buildings incorporate this technology. This difference may be attributed to design challenges or limitations in incorporating such plantings into existing structures. Further to evidence, the participant representing green retrofit building (PGRB3) pointed out that, “Though the client is really into green retrofitting, budget is a big deal for them. So, because of that, they can't really go for most of those advanced technologies”.

However, participants PGNB4 and PGNB8 mentioned that rain sensors were integrated into the buildings to conserve water by pausing any automatic cycles programmed after a sufficient amount of rain has accumulated. Thus, it helps to prevent overwatering of plants and saves water. To evidence, PGNB8, representing green certified new building mentioned that “The floor area of this building is over 20,000sq.m and it is a hotel building with 14-storeys, thus the operational cost of building is comparatively high, thus we particularly chose this technology disregarding its high investment to reduce the operational cost and water”. Additionally, majority (13 out of 18) of the surveyed buildings including certified and non-certified have regular 3rd party inspection and audit programs for monitoring the efficiency of water consumption. Some certified buildings also reported the use of smart meters to remotely control water usage, providing alerts for overconsumption and facilitating data comparison.

4.1.2 Lighting technologies

The survey conducted alongside the review identified seven distinct technologies that are commonly utilized in buildings to achieve lighting energy efficiency. These technologies are implemented to reduce the consumption of energy while maintaining the desired lighting levels in a building. Among them, LED lighting emerges as a universally embraced energy-efficient choice, present in all surveyed buildings irrespective of their green certification status. Therefore, it can be used in any type of building to maintain the energy-efficiency. Similarly, the majority of respondents (10) mentioned that they have considered compact fluorescent lamps as one of the lighting technologies to reduce electricity bills. When looking at the certification level, five (out of 11) green-certified buildings and five (out of 7) non-certified buildings use this lighting. This validates that compact fluorescent lamps can be effectively utilized in buildings that prioritize energy sustainability.

None of the non-green buildings have incorporated daylight-linked lighting control systems, occupancy-based lighting control systems, and light pipe technology. However, with the exception of daylight-linked lighting control, these technologies were integrated into a limited number of green-certified buildings. This underscores the significance of daylight-linked lighting control systems in promoting green certification and the limitations in the adoption of occupancy-based lighting control systems, and light pipe technology in Sri Lankan context.

Task lighting, designed to enhance occupant comfort and reduce eye strain, was implemented in ten (out of 11) green-certified buildings and four non-green buildings. The widespread use of task lighting in office and institutional buildings, but its absence in hotel buildings, indicates that its selection is closely linked to building functionality.

In one specific case, GNB8, a large hotel, adopted time-scheduled lighting control to enhance guest experience and optimize operational efficiency. This investment, though costly, was justified by the specific needs of the building function.

4.1.3 HVAC systems and control technique

As seen in **Table 3**, the survey has identified 10 different technologies used in buildings to achieve HVAC energy efficiency, which are in line with those obtained in literature. Compared to water efficiency and lighting technologies, the implementation of HVAC system technologies in buildings is comparatively low in Sri Lanka.

Among the surveyed buildings, 15 out of 18 have implemented optimum start/stop controllers, a widely adopted technology across all green retrofit buildings (GRBs) and green new buildings (GNBs). This indicates the emphasis on energy-efficient HVAC operations in certified buildings. Two of the three GRBs also incorporated free cooling appliances. According to the building representatives (PGRB1 and PGRB2), these appliances played a crucial role in obtaining green certification. However, PGRB3 noted the high capital cost as a challenge, stating, "Even though we had a choice to select free cooling appliances, the capital cost is very high." This highlights both the energy efficiency benefits and financial challenges associated with the implementation of free cooling technologies.

Among the non-green buildings, there is a notable absence of certain energy-efficient technologies, including load shedding and scheduling processes, demand control ventilation, variable refrigerant volume (VRV), energy-efficient chillers, and motorized louvers for heat control. In contrast, a subset of green-certified buildings has embraced technologies such as load shedding and scheduling processes, along with demand control ventilation. However, none of the existing green buildings have implemented demand control ventilation, and only GRB1 has incorporated load shedding and scheduling processes. This derives from a perception that green certification has influenced the incorporation of load shedding and scheduling processes, and demand control ventilation in new buildings. The case of GRB1, with its considerable size (39 storeys and the floor area of 70,000 sq.m), necessitates the adoption of load shedding and scheduling processes to manage the overall system load efficiently. Participant PGRB1 emphasized the significance of this technology, stating, "HVAC accounts for up to 40% of the building's energy consumption, so we had to reduce energy use. However, since the retrofitting occurred 17 years after construction, incorporating this system presented significant design challenges. We now have a building automation system integrated with load shedding". This case demonstrates how large existing buildings with high operational costs can still benefit from advanced HVAC technologies, even though implementation may be complex.

Despite the recognition of rotary heat wheels and heat pipes, energy recovery ventilators (ERVs) as a green retrofit technologies in the literature, none of the surveyed buildings, incorporated them. Respondents attribute this lack of adoption to the perception that these retrofit techniques are deemed ineffective in tropical climates, like that of Sri Lanka, where there is minimal variation in ambient temperatures between night and day. This insight aligns with both survey findings and existing literature.

4.1.4 Building envelope technologies

Along with the literature, the survey has identified 12 different building envelope technologies. Of them, technologies like low emissivity glass doors/windows, window shutters and window shade were available in all the surveyed buildings. The widespread implementation of these three technologies in both green-certified and non-certified buildings underscores their universal applicability, making them practical and adaptable choices for a variety of architectural contexts, regardless of green certification.

Notably, cool roofs, solar shading elements, green roofs and green walls were exclusively prevalent in green-certified (both new as well as retrofit) buildings. This indicates a strong correlation between green certification and the adoption of these specific building envelope technologies, as none of the non-certified buildings (7 out of 7) implemented them.

Technologies such as low emissivity glass doors/windows, window shutters, window shades, low conductive frame doors/windows, solar photovoltaic systems and solar shading elements in the wall were implemented in all three retrofit buildings (GRBs), prove their adaptability by blending with existing structures during retrofitting projects. These technologies are commonly associated with new green construction (GNBs) as well. While two of the retrofit buildings incorporated green walls and cool roofs, the third opted for green roofs. None of the retrofit buildings included opaque ventilated facades while these are integrated into green-certified new (GNBs) buildings. This distinction underscores the different challenges and considerations in retrofitting existing buildings versus designing new sustainable buildings.

Despite Nano insulation being recognized in the literature as a green retrofit technology, none of the surveyed buildings contained such technology. This is attributed to the perceived lack of necessity in the Sri Lankan context, where the prevailing climatic conditions do not warrant the utilization of this specific insulation technology.

4.1.5 Indoor environmental quality technologies

Along with literature, the survey has identified 08 different technologies used in buildings to achieve indoor environmental quality. Of them, light-colored paints were available in all the surveyed buildings. Majority of the green certified buildings (GBs) (10 out of 11) have incorporated ample ventilation for pollutant & thermal control and cross ventilation, while only 3 (out of 7) non-certified buildings (NGBs) have incorporated these technologies. Particularly, most of the office (10 out of 12) and institutional (3 out of 3) buildings have implemented cross ventilation technology, while none of the hotels (3 out of 3) incorporated the said technology.

Participants emphasized the importance of cross ventilation in educational and office buildings for improving air quality and reducing energy consumption by minimizing the need for mechanical ventilation. However, retrofitting high-rise buildings with cross ventilation posed challenges due to their vertical structure and limited access to outdoor air.

4.1.6 Sustainable site technologies

Of the literature identified technologies respective to this category, the survey has identified 04 different technologies used in buildings to achieve sustainability. Compared to other technology classifications, the adoption of sustainable site technologies was notably lower across the surveyed buildings. Participants cited a lack of external space and maintenance challenges as the primary reasons for not adopting these technologies. All the available sustainable site technologies in surveyed GRBs were integrated during the retrofitting process. None of the NGBs have incorporated these technologies, emphasizes the necessity of these sustainable site technologies in green certification procedures.

Roof-top gardening is specifically embraced by GRB2 and green new buildings GNB1, GNB2, GNB3, GNB4, and GNB8. The participant PGRB2 mentioned “During the retrofitting process for green certification, we incorporated a green roof and roof garden, as the design allowed. The upper roof is a lightweight structure covered with plants. The surrounding area is a rooftop garden with a viewing area”. Participants from the green new buildings noted that installing roof gardens was much simpler in new constructions compared to retrofits.

Cool pavement was adopted in one retrofit building (GRB1) after a detailed site analysis, demonstrating its potential in retrofit projects when space and design considerations align. Further, vertical gardening is incorporated in GNB3, GNB4 and GNB8. Remaining green building representatives opined that due to the high initial investment including the cost of materials, plants and irrigation system, it could not be feasible in those buildings. Moreover, participants PGRB1, PGRB2 and PGRB3 mentioned that there are many design difficulties in incorporating vertical gardening, thus they select traditional gardening methods over vertical gardening.

4.2 Challenges and barriers to integrating Green retrofit technologies

Following the survey of technologies implemented in the selected buildings, the participants representing the selected buildings were interviewed to identify the challenges that have influenced the adoption of particular technologies. The participants were facilitated with challenges identified under five categories: market, political, financial, green material and technological and performance challenges. **Table 4** tabulates the opinions of participants on the challenges encountered when implementing green retrofit technologies in the surveyed buildings.

4.2.1 Market challenges

The data summarized in **Table 4** reveals a prevalent issue of inadequate understanding and awareness of green retrofit practices among surveyed buildings, potentially leading to the failure to meet market expectations. Notably, this challenge extends across various types of buildings: all three green retrofit buildings (GRBs), all seven non-certified buildings (NGBs), and three (out of 8) certified new buildings (GNBs) reported encountering this issue. This highlights that insufficient knowledge and awareness of green retrofitting are widespread concerns, particularly among existing and non-certified structures, compared to newly certified constructions. Further, eight (8) of the surveyed buildings which were integrated green retrofit technologies before 2015 faced the scarcity of performance data and a lack of market consensus on leading green standards in the country. As a result, this summarized table reflects that a significant amount of market challenges have been mitigated over the years as a consequence of greater awareness and knowledge of green and green retrofit principles.

4.2.2 Political challenges

Amongst the surveyed buildings, GRB3, GNB1, GNB6, GNB7 and NGB3 are public buildings belonging to the government. As a result, the political challenges faced by governmental buildings are comparatively less than non-governmental buildings. Tax and regulatory incentives emerge as a prominent concern across all building types, with inconsistent implementation noted in several instances. Deficiencies in monetary incentives are also highlighted, particularly among GNBs (4 out of 8) and NGBs (2 out of 7). Furthermore, insufficient government and private sector investment and engagement are identified as significant obstacles, particularly affecting GRBs and GNBs. Moreover, the presence of incentives with unknown expiry dates adds complexity to the decision-making process, with implications for all building categories. However, the political challenges faced by green buildings have diminished over the years is one of the findings in the study. It emphasizes the importance provided by the government towards the green concept in recent years.

4.2.3 Financial challenges

As per the literature findings, financial challenges are considered the main barrier to the implementation of green retrofit technologies[39]. It was ascertained in **Table 4**. High initial capital costs are identified as a significant barrier across all building types, reflecting the substantial investment required for green retrofitting and new green construction. Additionally, inadequate funds present a prevalent challenge, affecting the ability of all building categories to finance sustainable initiatives. The majority (12) of the respondents agreed that there was an inadequate understanding of the lifecycle cost of green retrofit technologies during the implementation process. Furthermore, this was highlighted as a primary issue for GRBs (2 out of 3) and NGBs (7 out of 7), indicating a need for improved financial studies in these sectors. Transportation costs and price fluctuations also emerge as concerns, particularly impacting GNBs and NGBs. Moreover, economic recessions are noted as a specific challenge for GNBs, further complicating financial planning and implementation.

Table 4. Challenges encountered while implementing Green retrofit technologies

		GRB			**GNB**								**NGB**							
	Challenges	GRB1	GRB2	GRB3	GNB1	GNB2	GNB3	GNB4	GNB5	GNB6	GNB7	GNB8	NGB1	NGB2	NGB3	NGB4	NGB5	NGB6	NGB7	Total
Market	Inadequate understanding and awareness of green retrofit	√	√	√	√	√	√	-	-	-	-	-	√	√	√	√	√	√	√	13
	Possibility of failing to meet market expectations	√	√	-	-	√	√	√	-	√	√	√	√	√	-	√	-	√	√	13
	Scarcity of performance data	√	√	-	-	√	√	-	-	-	-	-	√	-	-	√	-	√	√	08
	Lack of market consensus on leading green standards	-	√	√	√	-	-	√	-	-	-	-	√	-	-	√	-	√	√	08
Political	Tax and regulatory incentives are not consistent	√	√	-	√	-	√	√	√	√	√	-	√	-	-	-	√	√	√	12
	Deficiency of monetary incentives	√	-	-	-	√	√	√	√	-	-	-	√	-	-	-	-	-	√	07
	Insufficient government and private sector investment and engagement	√	-	-	√	-	√	√	-	-	-	-	-	-	-	-	-	√	-	05

Financial	Incentives with unknown expiry dates	√	-	-	-	√	√	-	√	-	-	-	-	-	-	-	-	-	-	04
	High initial capital cost	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	18
	Inadequate funds	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	18
	Inadequate understanding of lifecycle costs	-	√	√	-	-	√	√	√	-	-	-	√	√	√	√	√	√	√	12
	Transportation cost	-	√	√	-	√	√	-	-	√	√	√	√	√	√	√	-	-	√	12
	Price fluctuations*	-	-	√	-	-	-	-	-	√	√	√	-	-	√	√	√	-	-	07
	Economic recession*	-	-	√	-	-	-	-	-	-	-	√	-	-	√	-	-	-	-	03
Green material and Technological	Maintenance difficulties*	√	√	-	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	17
	Implementation difficulties*	√	√	√	√	√	√	-	√	-	-	-	√	√	√	√	√	√	√	14
	The performance of new materials is not evaluated over time	-	-	-	√	√	√	√	√	√	-	-	√	-	-	√	√	√	√	11
	Spare parts availability*	√	-	-	√	√	√	√	√	√	-	-	-	-	-	√	√	√	√	11
	Insufficient supply of green materials and technologies	√	√	-	√	√	√	-	-	-	-	-	√	-	-	-	-	-	√	07
	Unreliable or unproven technology	-	-	-	√	-	-	-	-	-	-	-	√	√	√	√	-	-	√	06
Performance	Various considerations throughout the decision-making process for introducing green technology	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	18
	Insufficient supply of knowledge and training	√	√	√	-	√	√	√	-	√	-	-	√	√	√	√	√	√	√	14
	Professionally trained design teams are challenging to obtain	√	√	-	√	√	√	√	-	-	-	-	√	√	√	√	√	√	√	13

	Lack of awareness existing among the client*	-	√	√	-	-	-	-	-	-	-	-	-	√	√	√	-	√	√	07
	Barrier to the building's operations*	√	√	√	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	03

1*: Additional challenges identified from the Survey; GNB: green certified new buildings; NGB: non-green certified buildings.

4.2.4 Green material and Technological Challenges

Green material and technological challenges did not significantly impact the buildings compared to other categories of challenges during the implementation of green retrofit technologies. However, maintenance difficulties emerge as a prominent concern across almost all building types (17 out of 18), indicating the challenges in sustaining green technologies over time.

Implementation difficulties are also widespread, particularly affecting GRBs (3 out of 3) and NGBs (7 out of 7). The lack of long-term performance evaluation for new materials is highlighted as an issue primarily for GNBs (6 out of 8) and NGBs (5 out of 7). The rationale behind this trend lies in the necessity for GNBs and NGBs to carefully consider material utilization from the initiation of the construction process. Unlike retrofit buildings, which have limited flexibility in changing material types, GNBs and NGBs have the opportunity to select and integrate materials based on long-term performance considerations. Therefore, the lack of comprehensive evaluation for new materials in these buildings underscores the importance of careful planning and assessment processes to ensure the durability, efficiency, and sustainability of construction materials over time.

Furthermore, spare parts availability poses challenges, especially for GRBs (1 out of 3) and GNBs (6 out of 8), impacting the maintenance of green technologies. In certain instances, they purchased the spare parts from foreign countries with higher shipping expenses. Insufficient supply of green materials and technologies is noted as a concern across all categories, suggesting a need for improved access to sustainable resources. Despite these challenges, the study found that many issues have diminished over time, with improvements in the supply chain and material availability. However, questions around the reliability and effectiveness of green technologies persist, particularly among NGBs (5 out of 7), underscoring the importance of testing and validation processes. Improvements in these areas may significantly contribute to fostering a greater willingness among NGBs to incorporate green technologies and pursue certification in the future.

4.2.5 Performance challenges

As shown in **Table 4**, each surveyed building encountered difficulties during the decision-making process for implementing green technology underscoring the complexity involved in integrating green technologies. Further, the table validates the literature findings that still there is a lack of supply of knowledge and professionally designed teams for the green retrofitting process[1,14]. Insufficient supply of knowledge and training is also a prevalent issue, in the majority of the buildings (14 out of 18), highlighting the importance of enhancing education and skills development in the industry. Additionally, the difficulty in obtaining professionally trained design teams poses a barrier to effective implementation, impacting all building categories. Lack of awareness among clients is noted as a challenge only for GRBs (2 out of 3) and NGBs (5 out of 7), suggesting a need for improved communication and client education regarding the benefits of green technologies. Additionally, the participants from GRB1, GRB2 and GRB3 stated that the major challenge they faced during the integration process of green retrofit technology was a barrier to their functioning and operation of the building.

5. Conclusions

The aim of the study was to examine the selection of green retrofit technologies in various non-domestic buildings. Through an in-depth literature review and survey of 18 non-domestic buildings, a comprehensive set of 54 distinct technologies were identified and categorized into seven primary areas: water-efficient technologies (11), lighting technologies (7), HVAC systems and control technologies (10), building envelope technologies (12), indoor environmental quality (IEQ) technologies (8), sustainable site technologies (4), and other (2). The findings demonstrate that, while significant progress has been made in integrating these technologies, the adoption of these technologies remains limited, particularly in non-green certified buildings. Certain technologies were universally adopted across both green-certified and non-green buildings, highlighting their adaptability in various architectural contexts. These include low-emissivity glass doors/windows, window shutters, window shades, low-flow plumbing faucets, low-flow shower and water closets, dual flushing toilets, less capacity cistern tanks, LED lighting, and task lighting. On the other hand, more advanced technologies were predominantly found in green-certified buildings. In retrofit projects, technologies like free cooling appliances, optimum start/stop controllers, and load shedding and scheduling processes were particularly favored due to the operation benefit requirement of existing structure. Non certified buildings, however, mostly incorporated more basic technologies, such as compact fluorescent lamps and standard HVAC systems without advanced energy control mechanisms.

Challenges associated with green retrofitting, such as high initial costs, lack of awareness, inconsistent incentives, and inadequate access to green materials, continue to impede progress. Particularly, issues related to maintenance difficulties and the long-term evaluation of new materials highlight the complexity of integrating advanced technologies into existing structures. Political and financial barriers, including fluctuating tax incentives and insufficient government support, further contribute to the slow adoption of green retrofits.

However, it is worth noting that the survey was unable to investigate a larger number of buildings and equal distribution between the building types. This may have skewed the result; hence caution is required in the generalization of the study findings across Sri Lanka. Further research will be necessary to cover this inadequacy. Ramping up related sustainability studies, could help create the necessary awareness to Sri Lanka practitioners, to seek effective technological solutions for their sustainable green retrofits.

Declarations

Authors contribution

Sachchithananthan M: Writing–original draft, Literature survey, Data Analysis, Visualization.

Ramachandra T: Writing–review & editing, Validation, Supervision.

Thayananth M: Literature survey, Data collection.

Rotimi JOB: Writing–review, Validation.

Conflicts of interest

The authors declare no conflicts of interest.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Funding

Not applicable.

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