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Simulation of the Energy Performance of a Building with Green Roofs and Green Walls in a Tropical Climate

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Abstract: Global temperatures have continued to rise for decades, partly due to human-caused greenhouse gas emissions and subsequent urban heat island (UHI) effects. This current research examines the benefits of urban greenery by studying the impact of green roofs and walls of a building on thermal behavior and heat transfer in a warm and humid climate. This simulation study discusses the importance of greening systems in improving thermal comfort and minimizing the causes of UHI by assessing an integrated green building design. Using the simulation software DesignBuilder, the significance of greening systems, green roofs, and walls in enhancing thermal comfort and reducing the factors that contribute to UHI is investigated. The simulation results are based on the building's energy usage in hot and humid regions while featuring green roofs and walls. The simulation results indicate a considerable positive impact of greening systems in improving the urban environment in hot and humid tropical climates. Air temperature, radiant temperature, humidity, and solar gain are decreased by urban greening. The total energy consumption and district cooling demand of buildings with green roofs and walls are reduced by 10.5% and 13%, respectively. The greening systems substantially improve air quality and building's energy efficiency. Thus, the present study's findings can benefit urban designers and dwellers in devising strategies for establishing green spaces in congested urban environments by integrating green technologies and systems into built environments.

Keywords: green buildings; urban climate; low-energy buildings; green roof; green wall; urban heat island; thermal comfort; passive urban design; tropical regions; energy consumption

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1. Introduction

Buildings and construction industries account for over one-third of global energy usage and approximately 40% of total CO_2 emissions. Construction-related energy consumption is continuously increasing due to rising energy requirements in developing nations, according to International Energy Agency, 2013. Several countries have established novel and stringent measures to improve building efficiency and lower energy usage to fulfill the long-term greenhouse gas (GHG) reduction targets of 2050 (European Commission 2014, a policy framework for climate and energy). United Nations Sustainable Development Goal 11 can be met by urban greening to address urban density and subsequent challenges [1]. Green infrastructure's environmental, social, and economic advantages, such as green roofs and walls, extend well beyond the building itself. The use of urban greening enhances the thermal and visual comfort and the psychological health of inhabitants.

Environmentally friendly transportation infrastructure is a top priority for city planners and policymakers [2]. Sustainable Development Goal 11 may be partly achieved using greening solutions such as green walls and roofs. Integrating greenery into the urban scenario includes several social, economic, and environmental advantages [3,4]. Weather and local climate are also major considerations. Green roofs and walls have been demonstrated in studies to lower the summer peak temperature under the roof membrane in various settings, from temperate to tropical. On the other hand, green infrastructure minimizes winter heat loss, making it a feasible alternative even in frigid locations. In addition, studies have shown that they can prevent heat loss through the roof and walls in cold winter climates.

Extreme heat-liberating activities raise the temperature inside buildings. Thus, more energy usage increases environmental pollution and results in subsequent health issues [5]. Combined night ventilation, shade in the building envelope (e.g., trees, climbers, or green walls), light color coatings, thermal insulation, and an upgraded roof are passive solutions for reducing heat gain in built spaces [6]. These measures can help increase heat resistance and improve the interior environment's thermal comfort while also reducing power usage during the year's warmest months. Many architectural practitioners have attempted to mitigate the widely prevalent issues of rising GHG emissions and climate change with the deployment of innovative green designs that save energy, lessen pollution, and promote sustainability. The psychological and environmental advantages of green infrastructure in cities are multiplied by their ability to mitigate the adverse effects of UHIs and climate change. Green envelopes are sustainable solutions to combat the problems of UHI such as higher levels of air atmospheric pollution and elevated temperatures that directly impact human health. Building thermal performance depends on inclusion of green elements, adoption of energy-saving measures, usage of shading devices, evapotranspiration, and provision of thermal insulation. Green roofs are made by growing plants in building envelopes using multilayered techniques to improve the thermal comfort of buildings.

Green roofs can be implemented in various styles and formats. Each technique may incorporate various design elements, such as diverse plant species and substrate compositions. Herath et al. [7] undertook an investigation using the simulation software ENVI-met to study the impact of installation of greening systems on the energy use of buildings. The green roofs, green walls, and combining all the strategies reduced the temperature by 1.87 °C, 1.79 °C, and 1.90 °C, respectively. The urban greening strategies of green envelopes are essential for reducing GHG emissions and lowering building-related energy consumption. Green envelopes minimized the heat transfer through building roofs by up to 80% [8]. Greenery systems with vegetation provide aesthetically appealing and thermally comfortable indoor and outdoor environments.

The energy needed to heat or cool a building is directly related to its thermal inertia [9]. Increased thermal comfort and reduced energy usage can be achieved by using construction materials with a thermal mass on the internal surface of thermal insulation in buildings. The prevalence of UHI and global climate change has led to greater awareness of the need for urban greening to reduce heat in urban areas and improve thermal comfort [10]. The rapid urbanization trend witnessed in years has replaced vegetation and open areas with complex and impermeable surfaces, resulting in negative impacts on urban ecosystems worldwide. The efficacy of green buildings depends on the selected plant species and local environmental factors. The optimal planning, design, and integration of urban green spaces into the built environment are challenging. Earlier research studies have primarily concentrated on the speed of air cooling by urban green infrastructure and its influence on thermal comfort on small temporal and spatial scales [11,12].

Weather conditions have a tremendous influence on human comfort in outdoor areas. Unfavorable outdoor environments with severe climatic conditions may discourage outside activities and increase energy demand in interior spaces. Hence, it is critical to assess and implement thermal adaptation solutions to offer adequate indoor thermal comfort conditions for urban dwellers [13]. The adaptation to the outdoor climate paradigm includes three groups of adaptive strategies: environmental and technological adaptations, behavioral adjustments, and psychological adaptation. In urban settings, green envelopes can offer various ecosystem services while being robust and adaptable [14,15]. Most researchers have shown a preference for environmentally friendly solutions over conventional ones for promoting a healthy urban ecosystem [16,17]. The economic assessment increases when environmental and social advantages are included. The existing research reveals that balancing the costs and advantages of building green structures plays a significant role in their widespread deployment [18,19].

Ecological infrastructure such as green envelopes introduced in highly populated metropolitan regions can improve urban environments by reducing GHG emissions as they reduce energy usage in buildings [20–22]. Natural greening systems provide significant advantages over standard grey alternatives, particularly in high-density urban zones. More than 54% of the global population already resides in urban areas, which is projected to escalate to 66% by 2050 [23]. The benefits and effectiveness of integrating green infrastructures, such as green building envelopes with urban architecture, are now well recognized. The system is being implanted in many cities worldwide [24,25]. The functioning of the greening system requires minimal monitoring after installation on a building envelope. Most cities throughout the globe have been plagued by poor air quality for a long time, and green facades can help improve air quality by lowering pollution levels [26]. Greening infrastructures such as green envelopes have several substantial environmental advantages, including the capability to trap and remove ambient pollutants in densely populated urban areas, restore air quality, and improve the urban environment [27–30].

According to research conducted on historic Iranian dwellings, people built structures on a soil mass to retain heat and lower heating and cooling energy costs. The occupants of a building can benefit from optimal temperature conditions by establishing a balanced microclimate [31]. The thermodynamic properties and efficiency of vegetation covers were investigated using a finite difference simulation model [32]. Plants significantly influence the prevailing climate through their photosynthesis and transpiration processes. Foliage shields buildings from solar radiation, regulates the indoor environment's temperature and humidity, and shelters buildings from winds. Root zone air temperature is lower in enclosed structures covered with vegetation. The heat transmission process in plant-integrated building envelopes is entirely different from that of a conventional one sans greenery. The greening system lowers the temperature of the air moving over the surfaces of the building envelope.

The concept of the human-made ecosystem of green buildings is currently receiving considerable public attention, necessitating the formulation of regulatory policies and guidelines for green building projects [33]. The residents of Beijing had a good understanding of the many advantages of greening systems and were very supportive of green building initiatives and promotional efforts taken by the government. Sociodemographic characteristics, the living environment, and the attitude to greening initiatives were the three most important determinants of public opinion. Incorporating microclimate factors into urban planning practices and architecture improved energy efficiency and outdoor thermal comfort [34]. Due to their cooling effect on the indoor environment of built structures, living walls and vegetative roofs have recently emerged as green envelope technologies integrated with a building. This strategy helps reduce energy consumption for heating and cooling the building space. The combined influence of green roofs and green walls was shown to reduce cooling loads by as much as 36.8% when compared to the base case structure [35]. Green walls can be actively used in building systems as biological filters. They help purify the ambient air, improve air quality, and serve as an active building ventilation system. However, the dual-use potential of green walls lies both within and outside a built structure [36]. Excellence in constructing green façades comes from the rapid green cover provided for a building and the ease of replacing or modifying the greening. Green façades positively impact the indoor built environment and offer significant ecological benefits. Vertical and horizontal shade contraptions placed in the north and south directions can fill the free area between metal structures and walls.

The vertical greening system prototype improved interior thermal comfort levels and provided a substrate for growing medicinal plants and culinary herbs. It decreased interior air temperatures by an average of 2.3 °C, bringing internal comfort conditions to the ideal zone 90–100% of the time [37]. Sustainable and environmentally friendly green walls have positively impacted urban microclimates [38]. Although enhanced productivity and visual attractiveness are predicted benefits of green roofs and walls, this would only apply if visible from windows in surrounding buildings [39]. According to research, when viewed from different perspectives, nature can increase visual attractiveness by 42% compared to urban construction materials [40]. Natural viewpoints enhanced quality of cognitive measures, lending credence to the proposed theoretical viewpoints [41]. Many building standards can be used for designing green infrastructure, such as the German Landscape Research, Development, and Construction Society (FLL) guidelines, green roofs for healthy cities, the ASTM Book of Standards, v. 04-12 (2005), Leadership in Energy and Environmental Design (LEED®), FM Global, BOCA Codes, the International Code Council (ICC), and Low-Impact Development (LID) Urban Design Tools [42].

High-density housing has become a vulnerability hotspot due to the rising urban heat. There must be alternatives to prolonged air conditioning [43]. Urban greening policies must consider how the public views the benefits and drawbacks of ecosystem services provided by urban greenery. Pollution, the urban heat island effect, noise, crowding, decreased biological diversity and heterogeneity, and a lack of and disconnection from nature are some of the main adverse effects. The extensive environmental degradation can significantly impact residents' quality of life, their physical and mental health, and the functioning of the urban ecosystem [44]. Some urban greenery has been elevated due to rapid urbanization and urban growth. The public school system could increase citizens' awareness of the advantages of environmentally responsible green roofing and the necessity for rooftop gardens to be user-oriented to accommodate particular potential users. Well-placed sites could lessen accessibility disparities in urban green space, particularly for lower-income individuals. This study helps to clarify how the public perceives the advantages of green roofs and their favored landscape features and designs [45].

Two distinct green roofing systems are available: extensive green roofs with smaller plants, and thin substrate layers and intensive green roofs with thick substrate layers and larger plants. Green roofs that shade building surfaces significantly benefit the environment by lowering temperatures, conserving energy in urban buildings, and mitigating the effects of UHI [46]. Green roofs over a building also reduce noise, provide a habitat for plants and insects, increase human productivity, enhance visual appeal, and reduce rainwater logging and lower pollution [47–49]. Green roofs enhance a building's energy efficiency through plants' evaporative cooling, shading, and insulating characteristics and the growth medium [50]. A rooftop garden can minimize the UHI problem in tropical cities with increased urban greenery by reducing the heat radiation problem. Rooftop gardens in Sri Lanka reduced temperatures by 10–15 °C [51]. When surface temperatures were tested in the field, they decreased to their lowest point of 18 °C after constructing an extensive green roof on a building in Singapore. The thin substrate layer, dark substrate color, and low-lying plants of the extended green roof system resulted in lower thermal efficiency than the intense green roof system. A thin covering of the spreading green roof rapidly released stored heat and offered better evening cooling. The entire greening system of the building reduced the heat gain by around 60% [52]. Green spaces in cities have important ecological benefits as they serve as natural habitats for all forms of biota while also providing for their needs. However, as the urban population surges and available land shrinks rapidly, green spaces such as green envelopes are becoming more widespread in metropolitan areas as open spaces are increasingly being taken up for real estate deployment [53].

The efficiency of different green infrastructures in attracting and promoting biodiversity is still restricted. With its ability to host and sustain urban wildlife, thus enhancing previously depauperate regions, green roofs, along with other urban green spaces, may have significant ecological value [54,55]. There is evidence that green roofs may boost cities' biological diversity if implemented widely [56,57]. Green roofs make recreational areas available, create a food supply, offer aesthetic benefits, promote good health, and serve as a contemporary architectural design for sustainability [58,59]. Green envelopes with vegetation increase the property's worth, reduce background noise, contribute to a more comfortable temperature in the environment, and reduce heating and cooling costs by improving a building's insulation [60,61].

Green walls with growing plants can help insulate the home, muffle external sounds, and boost a house's aesthetic value and appeal; in addition to luring birds, squirrels, butterflies, insects, and bees, the garden serves as a serene and comfortable place to take a rest [62,63]. Residential greening encompasses all possible measures such as green walls, roofs, and envelopes to improve the urban environment. Reducing heat islands lowers the energy consumption patterns of buildings and results in substantial energy savings [64,65]. The results of a reduction in energy consumption due to green envelopes are on par with the findings documented in the literature [66,67]. Green envelopes in a building minimize the pollution from burning fossil fuels for providing human comfort. The careful selection of appropriate types of plants and proper installation methods helps to minimize the initial investment and maintenance costs of residential and urban greening [68–71]. The connectivity infrastructures of urban areas are also responsible for UHI [72,73]. Buildings in tropical climates usually consume more power to cool the indoor built spaces making green roofs one of the feasible solutions to reduce heat penetration and lower energy consumption [74,75].

Several investigations have analyzed ways and means to improve buildings' thermal comfort using various green measures. However, increasing urban green spaces by combining green roofs and walls has not been discussed much from a cooling energy consumption perspective. The current simulation study investigates the thermal performance of a building with green roofs and walls using the DesignBuilder software tool. The present research work is organized into four comprehensive sections. Section 1 presents the background and the identified need for the present study. Section 2 discusses the materials and methods adopted in the simulation study. Section 3 covers the salient results and discussion. Section 4 summarizes the significant conclusions gathered from this study and the scope for extending the study in the future.

2. Materials and Methods

This simulation research study was conducted to examine the impact of conventional roofs, walls, and green envelopes on heat transfer through the walls and roof, as well as their energy efficiency in hypothetical multistoried commercial building blocks in Chennai's tropical climate (Latitude of 13° N and longitude of 80° E). Chennai, historically known as Madras, is the capital city of Tamil Nadu, India's southernmost state. It is the state's largest city in terms of land and population and is located on the Coromandel Coast of the Bay of Bengal, 52 feet above the mean sea level. As per Koppen's climate classification, Chennai falls under a tropical Savanna climate (Aw). The annual rate of increase in the population is about 2.4%. According to the Indian census, Chennai is the sixth-most populated city in India and the fourth-most populous urban agglomeration (11.5 million in 2022).

Figure 1a shows the adopted research methodology. DesignBuilder software was used to model conventional and green envelopes in the researched climate and associated materials. DesignBuilder software is a comprehensive program that creates a graphical interface for an EnergyPlus dynamic thermal simulation engine. The time interval considered in this simulation study was an entire year. The phase examined the heat transmission simulated by conventional and green envelopes using the DesignBuilder software tool. The meteorological data were entered into the DesignBuilder as a location file. This research study evaluated heat transmission over conventional and green envelopes in many stages for the city's tropical environment over 1 year. The final set of analyses used parameters such as air temperature, radiant temperature, relative humidity, solar heat gain, and site and end-use energy for district cooling.

Figure 1. *Cont.*

(c)

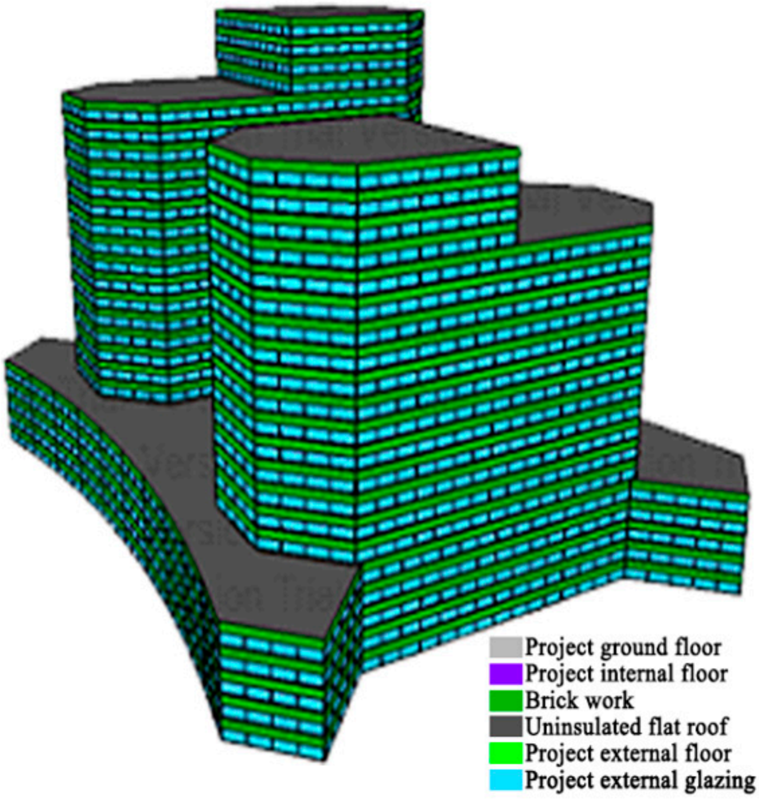

Figure 1. (**a**) Research methodology; (**b**) location of the study area; (**c**) building blocks.

The selected site's geographical coordinates were 13°5′16.2″ N and 80°16′42.5″ E, located in the warm and humid tropical climate prevailing in the metropolitan city of Chennai, as shown in Figure 1b. Figure 1c shows the simulation of the building blocks. Two hypothetical commercial buildings with actual specifications (with a floor area of 220,000 m^2) were simulated to study the enhancement in energy performance and thermal improvement by using urban greening infrastructure on the building. The gross area of the window opening of the building was 33,435 m^2. The gross window–wall ratio of the selected building was 49%. The total building wall area was 304,000 m^2. The green roofs and walls can be implemented on the terrace, patio areas, balconies, etc. In this hypothetical site, the building is in a tropical climate. The intense radiation from the sun is primarily from the east–west direction. Thus, the green walls can be implemented in the direction where there is intense solar radiation. The building block is an air-conditioned mixed-energy use building. The simulation was carried out using the annual weather data of Chennai with and without integrated green envelopes using standard conditions. This work conducted simulation research in DesignBuilder to perform the green envelopes' heat transfer performance. Conventional and green buildings were compared to obtain energy performance. Figure 2 shows the thickness and strata of conventional and green envelopes.

According to Figure 2, a conventional wall has three layers: plaster, brick, and plaster. A green wall has ten layers: plaster, wall air space as resistance, plaster, brickwork, air space cavity, plaster, PVC, felt, soil, and vegetation. A conventional roof has three layers: plaster, concrete, and asphalt. A green roof has seven layers: plaster, concrete, cement mortar, bitumen, natural rubber, mud, and vegetation from the inner surface to the outer surface. The leaf area index (LAI) and other prominent characteristics of green buildings used in building models are also based on the Chartered Institution of Building Services Engineers Guide A [35], as shown in Table 1.

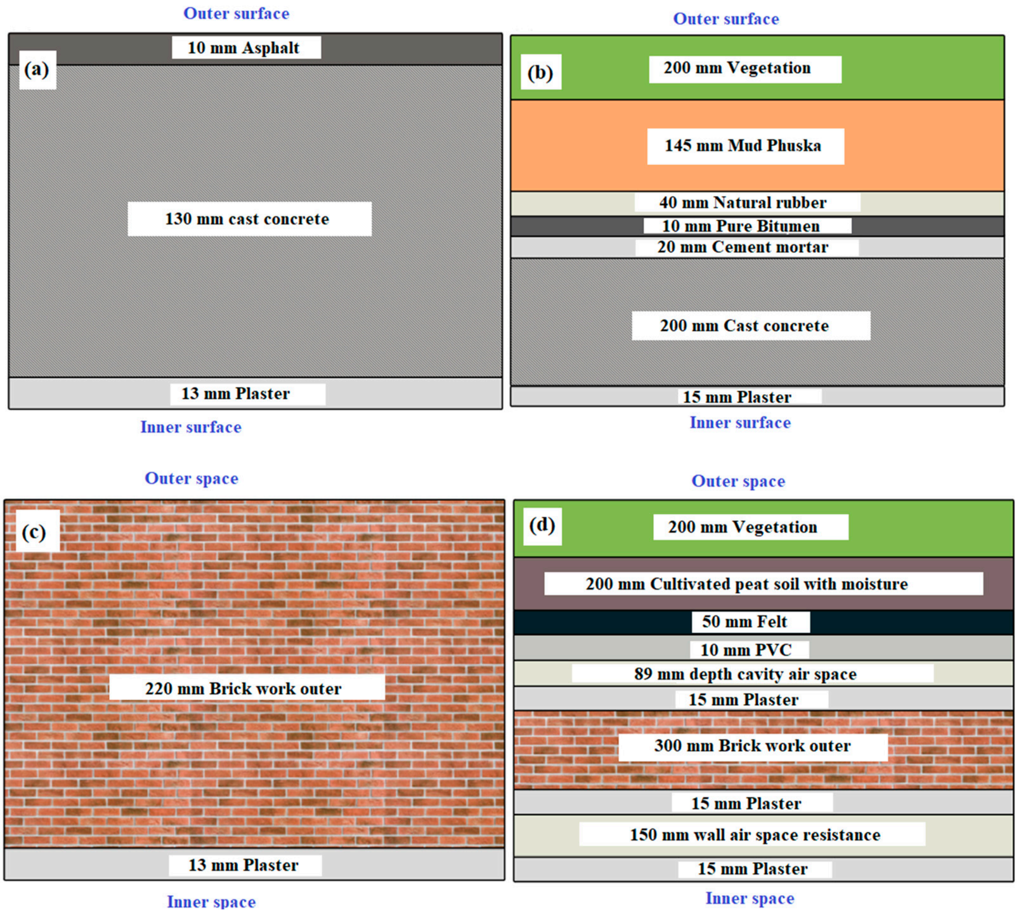

Figure 2. The thickness and kinds of strata in (**a**) conventional roof, (**b**) green roof, (**c**) conventional wall, and (**d**) green wall.

Table 1. Plant materials data used in this study [54] (Adapted with permission from [54], Elsevier, 2023, license number 5467560440955).

Plant Materials Data	
Grass/straw materials—straw thatch (m)	0.1
Thermal bulk properties	
Conductivity (W/m·K)	0.4
Specific heat (J/kg·K)	11
Density (kg/m^3)	641
Height of plants (m)	0.6
Green roof thermal parameters	
LAI	2.7
Leaf reflectivity	0.22
Leaf emissivity	0.95
Minimum stomatal resistance (s/m)	180
Max volumetric moisture content at saturation (%)	0.5
Min residual volumetric moisture content (%)	0.01
Initial volumetric moisture content (%)	0.15
Surface properties	
Thermal absorptance (emissivity)	0.78
Solar absorptance	0.6
Visible absorptance	0.6

The results of the comparative study of the heat transfer performance of conventional and green buildings are discussed in the next section.

3. Results and Discussion

Heat transfer data for the envelopes were extracted from the DesignBuilder software's cooling design section and are given in Figure 3 and Table 2. The mean values of the selected parameters of conventional buildings were observed to possess higher air temperatures, radiant temperatures, and solar heat gain through windows compared to green buildings. However, the relative humidity of air was observed to be higher for green buildings due to the evapotranspiration of plants. The air temperature in green buildings is about 2.37% lower compared to conventional buildings without greening systems.

Table 2. The range of values of the results of the current simulation study: (a) air temperature, (b) radiant temperature, (c) relative humidity, and (d) solar heat gain through exterior windows.

Roof and walls	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(a) Air temperature (°C)												
Green roof and walls	23.55–26.95	24.28–27.28	24.74–28.04	24.79–27.99	25.58–29.20	25.52–29.3	25.13–28.73	25.1–28.5	25.09–28.29	24.62–27.92	24.17–27.37	23.79–26.99
Standard roof and walls	24.21–27.61	24.79–28.29	25.35–28.95	25.76–29.36	26.29–29.89	26.42–29.82	25.83–29.23	25.65–29.05	25.71–28.91	25.25–28.45	24.48–28.08	24.12–27.72
(b) Radiant temperature (°C)												
Green roof and walls	25.08–29.08	25.61–29.61	26.11–30.11	26.71–30.71	27.13–29.13	26.94–30.94	26.7–30.7	26.49–30.49	26.4–30.4	26.08–30.08	25.51–29.51	25.16–29.16
Standard roof and walls	26.73–30.73	27.42–31.42	27.81–31.81	28.04–32.34	28.78–30.78	28.59–32.59	28.15–32.15	27.81–31.81	27.88–31.88	27.5–31.5	26.8–30.8	26.54–30.54
(c) Relative humidity (%)												
Green roof and walls	57.67–63.67	60.76–62.76	63.84–69.84	66.86–72.86	60.72–66.72	63.31–69.31	62.88–68.88	64.56–70.56	67.11–73.11	67.31–73.31	68.87–72.87	62.85–68.85
Standard roof and walls	55.54–59.54	57.15–61.15	61.05–65.05	64.06–68.06	58.4–62.4	60.81–64.81	60.89–64.89	62.7–66.7	64.65–68.65	65.01–67.01	65.83–69.83	60.94–64.94
(d) Solar heat gain through exterior windows (Wh/m^2)												
Green roof and walls	1017–1037	1016–1036	1125–1146	1087–1101	1094–1114	997–1017	913–933	900–918	932–952	930–940	834–854	890–910
Standard roof and walls	4232–4292	4001–4062	4035–4075	3701–3741	3781–3802	3590–3620	3329–3369	3203–3243	3340–3380	3525–3565	3385–3425	3733–3783

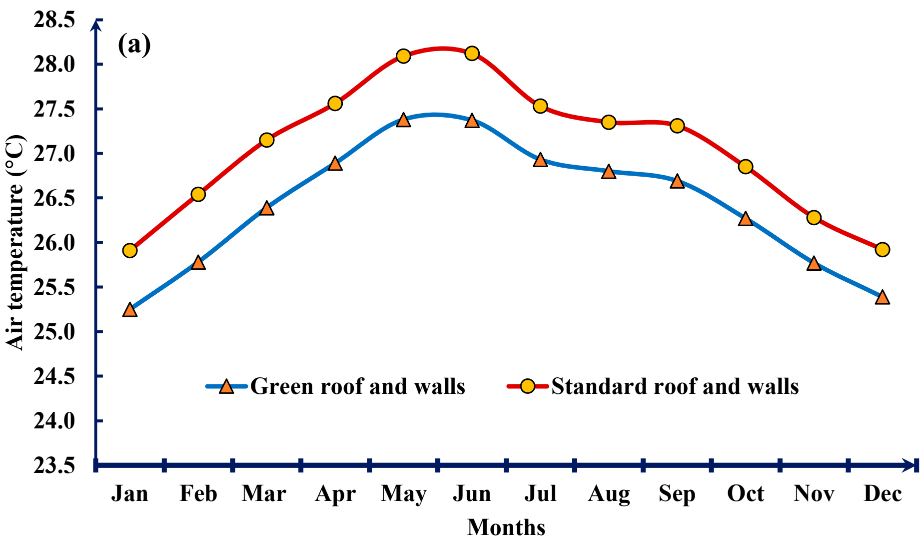

Figure 3. *Cont.*

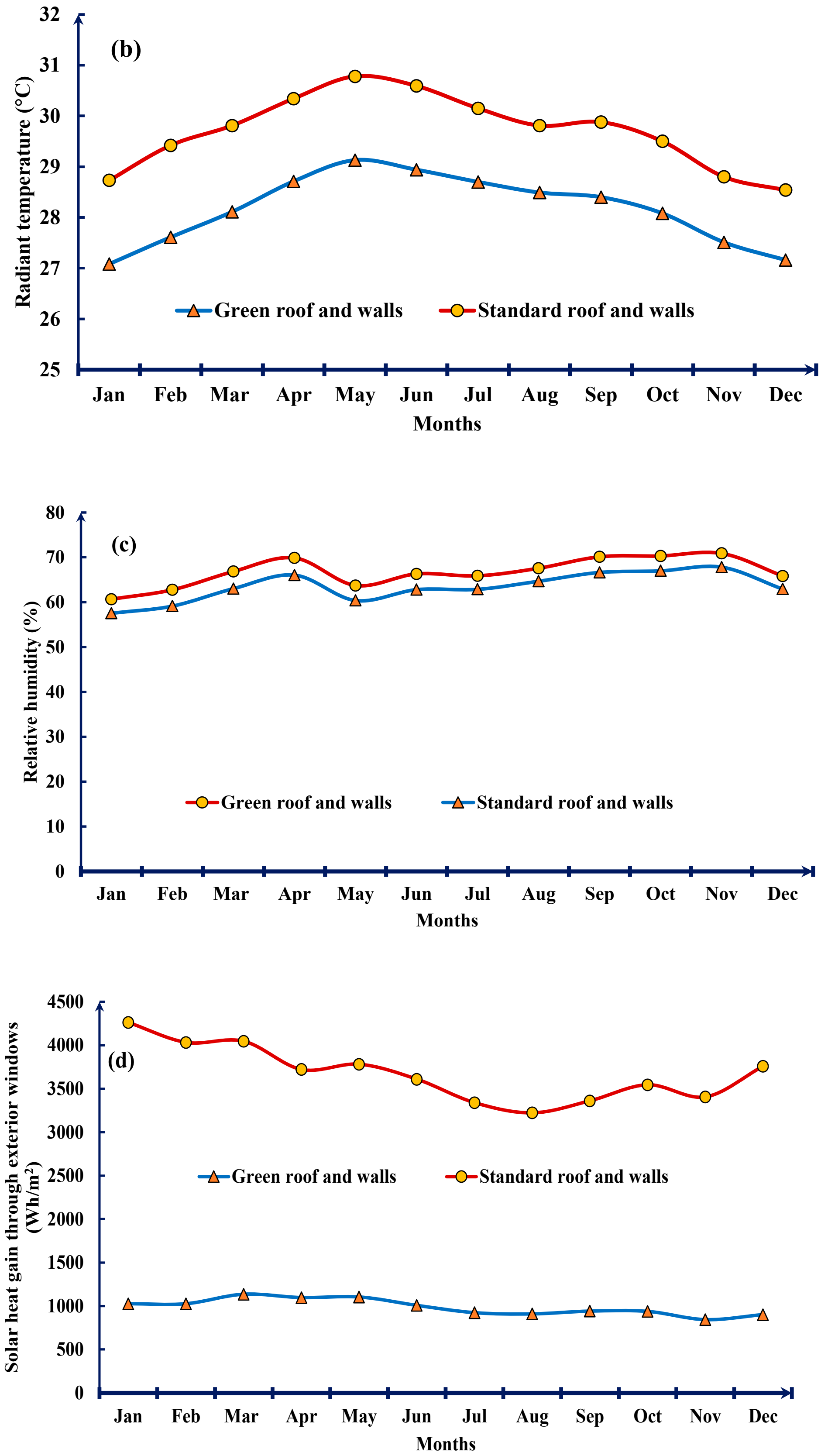

Figure 3. Comparison of the mean values of the current simulation results with green and conventional walls: (**a**) air temperature, (**b**) radiant temperature, (**c**) relative humidity, and (**d**) solar heat gain.

The radiant surface temperature in green buildings is about 5.17% lower compared to conventional buildings without greening systems. The green buildings' air relative humidity value was about 4.62% higher than that of conventional buildings. The solar heat gained through direct sun-exposed walls of the conventional building was observed to be about 70% more than the building with a green roof and a green wall of 200 mm thick-vegetation layer. The significant weather parameters affecting evapotranspiration were solar radiation, air temperature, moisture, and wind velocity. The plant selection and support structure must be selected with due care, ensuring that they are appropriate for the annual climatic variation at the site. Aloe vera, succulent plants, bromeliads, banana trees, hibiscus, palm trees, orchids, and other plants can be used in a tropical climate.

Detailed information on the thermal characteristics of the building envelopes is provided in Table 3 and Figure 4. Regarding wall configurations, the U-value surface to surface ($W/m^2{\cdot}K$) was found to be reduced to 0.241 (green wall) from 3.473 (conventional wall). The R-value ($m^2{\cdot}K/W$) was noted to be increased to 4.325 (green wall) from 0.458 (conventional wall), and the U-value ($W/m^2{\cdot}K$) was reduced to 0.231 (green wall) from 2.184 (conventional wall). Regarding roof configurations, the U-value surface to surface ($W/m^2{\cdot}K$) was observed to be reduced to 0.438 (green roof) from 3.035 (conventional roof). The R-value ($m^2{\cdot}K/W$) was noted to increase to 2.423 (green roof) from 0.469 (conventional roof), and the U-value ($W/m^2{\cdot}K$) was seen to be reduced to 0.413 (green roof) from 2.13 (conventional roof).

Table 3. Thermal parameters of the roofs and walls.

Parameters	**Wall**	**Roof**
Inner surface		
Convective heat transfer coefficient ($W/m^2{\cdot}K$)	2.152	4.46
Radiative heat transfer coefficient ($W/m^2{\cdot}K$)	5.54	5.54
Surface resistance ($m^2{\cdot}K/W$)	0.13	0.1
Outer surface		
Convective heat transfer coefficient ($W/m^2{\cdot}K$)	19.87	19.87
Radiative heat transfer coefficient ($W/m^2{\cdot}K$)	5.13	5.13
Surface resistance ($m^2{\cdot}K/W$)	0.04	0.04
No bridging—conventional walls and roof		
U-value surface to surface ($W/m^2{\cdot}K$)	3.473	3.035
R-value ($m^2{\cdot}K/W$)	0.458	0.469
U-value ($W/m^2{\cdot}K$)	2.184	2.13
No bridging—green walls and roof		
U-value surface to surface ($W/m^2{\cdot}K$)	0.241	0.438
R-value ($m^2{\cdot}K/W$)	4.325	2.423
U-value ($W/m^2{\cdot}K$)	0.231	0.413

Figure 5 shows the comparison of energy consumption in conventional and green buildings. The district cooling load of green buildings was reduced by about 13% compared to conventional buildings. The site energy requirement of green buildings was reduced by about 10% compared to conventional buildings. The green envelopes act as thermal insulation against solar radiation and minimize heat transmission into the buildings. Thus, green buildings reduce solar heat gain and minimize the power requirement for air-conditioning loads.

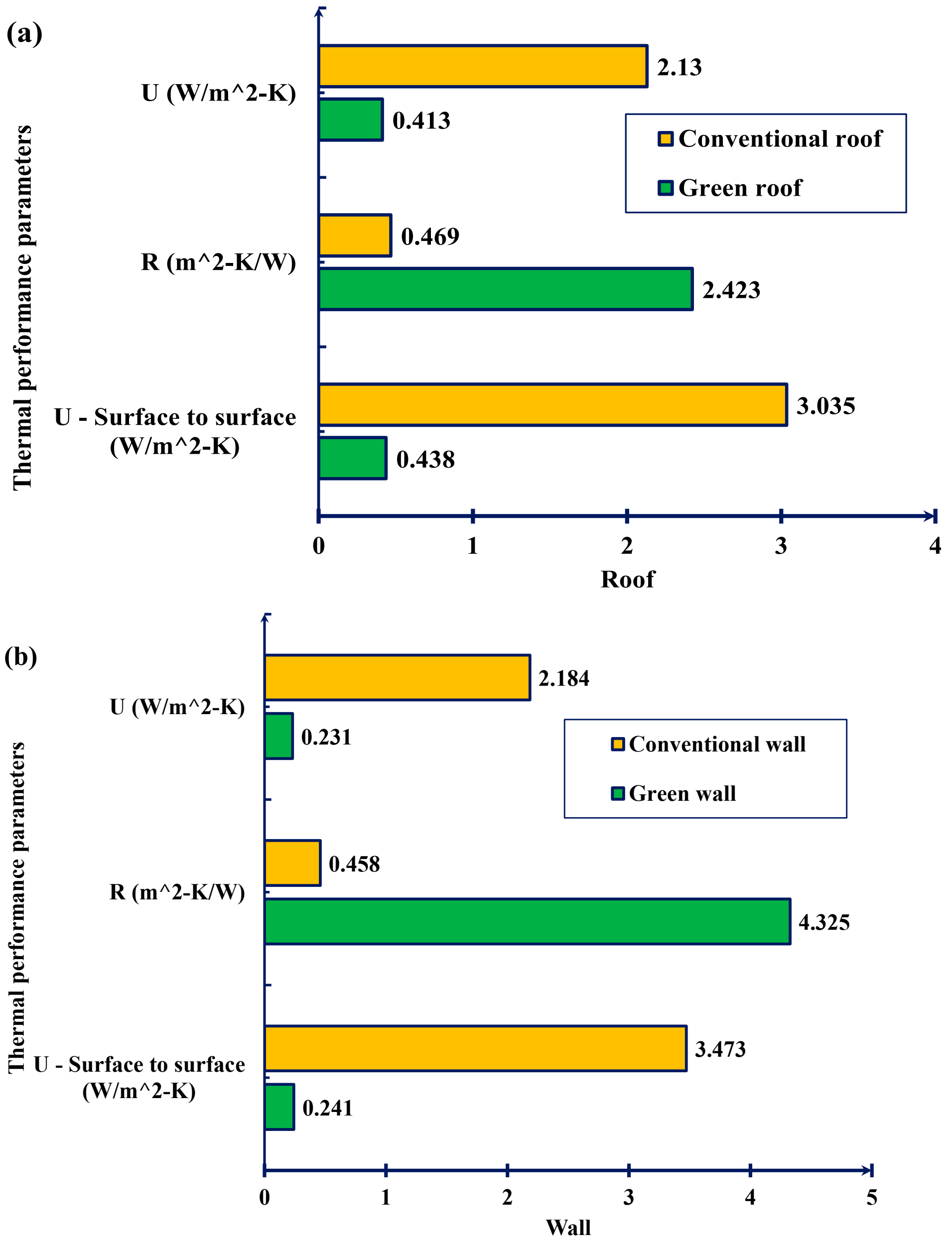

Figure 4. Comparison of thermal performance parameters of conventional and green envelopes from the current simulation study: (**a**) roofs; (**b**) walls.

The salient features of green envelopes are as follows:

- They help in minimizing the building's cooling and heating needs.
- They delay and decrease stormwater discharge.
- They offer better soundproofing and acoustics management.
- They contribute to capturing and storing CO_2 underground.
- They snatch up gaseous and particle contaminants from the ambient air.
- They mitigate the UHI effects.
- They help sustain and increase the life span of plants and animals.

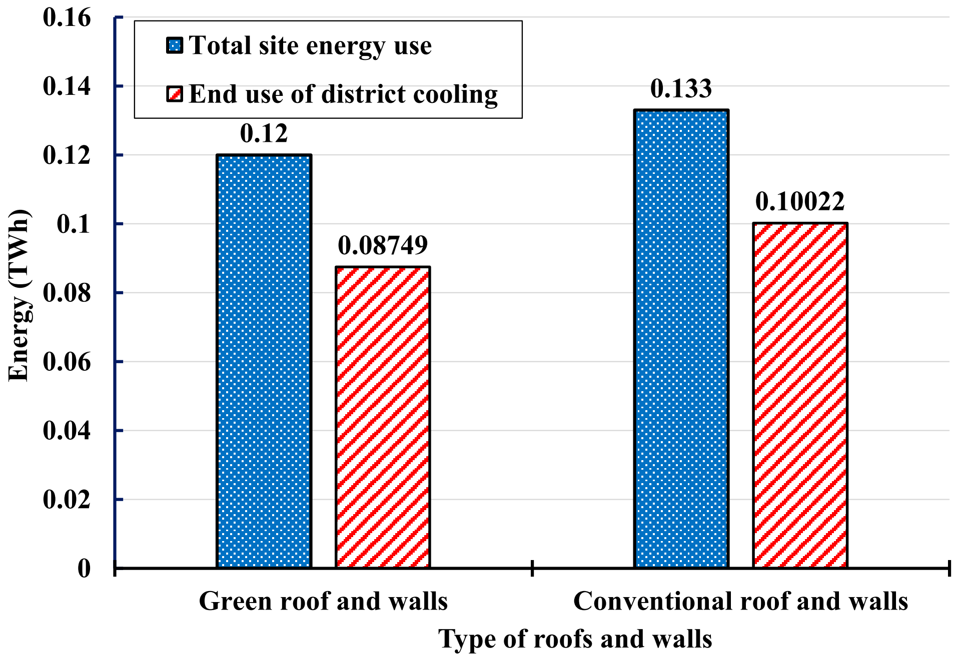

Figure 5. The current simulation study compared total site energy use and end-use district cooling loads with and without green roofs and walls.

Buildings that are equipped with green roofs and green walls reduce their carbon impact on the local environment. Greening technology allows better use of energy resources, facilitates safe building practices, results in more sustainable buildings, and enhances the quality of urban life by including natural surroundings in concrete-built spaces. Green structures are becoming more common by incorporating technologies that reduce the building's impact on its inhabitants and the environment throughout its lifetime. As plants reduce the maximum air temperature of the indoor environment, they make a building more bearable to spend time in during the hotter summer months. The lowest temperature of the inside air is unaffected, while the maximum temperature of the soil is increased with soil thickness. Energy simulation systems are increasingly used to evaluate a building's energy performance and occupants' thermal comfort.

The obtained results primarily depend on the building location (prevailing climate). The outcomes should not be limited to the temperature within a built structure but should also consider the surrounding environment. Multi-objective optimization studies can also be conducted to determine the optimal combination of all the variables under study. Rooftop and wall greening on larger and taller buildings would be a viable next step, as would in situ experimental validation of the proposed model. The pros and cons, as well as the challenges, of green roofs and walls may be better understood if they are classified on the basis of the type of planting systems. The maintenance aspect of green roofs and walls must be considered, as it is likely to be time-consuming and expensive.

Buildings have a tremendous impact on our health, as well as the health of future generations, by impacting both our external and internal surroundings. Because of the benefits, builders prefer green constructions to regular ones. Is it true that green buildings outperform conventional structures? Both conventional and green buildings appear identical from the outside. However, they are opposed to the technology employed and the advantages provided. The primary goal of green buildings is to decrease energy and water consumption, recycle trash, use environmentally friendly materials, etc. In contrast, conventional buildings are not often constructed with energy, water, material, or indoor comfort efficiency in mind.

The results obtained from the present investigation of the greening system of vegetated roofs and walls will be helpful in devising measures to effectively control and manage the cooling load requirements of buildings situated in tropical countries such as India. For extreme weather conditions, dynamic façade systems could better serve residents' thermal comfort needs by allowing solar radiation into the buildings in winter and restricting solar heat gain during summer. This research study indicates that a multidisciplinary approach must necessarily be adopted involving the concerted efforts of architects, engineers, and stakeholders to understand the multiple benefits of greening the building envelope before actual construction. According to the building simulation, the WWR was 49%. Therefore, only when there is a minimum of half the wall area would there be a difference in the parameters. Hence, while designing the building structure, we should keep in mind the WWR.

4. Conclusions

This current research comparatively evaluated conventional and greening-integrated buildings under the same tropical climatic conditions to analyze their cooling energy in hot and humid climatic conditions. The building envelopes' relative humidity, temperature difference, and solar gain are significant to a building's thermal performance. The main findings of the simulation study of conventional and green facades are stated below.

- A considerable thermal difference was observed between conventional envelopes and green envelopes.
- Compared to conventional buildings without green envelopes, green walls and roofs decreased the indoor air temperature, radiant temperature, and solar gain by 2.37%, 5.17%, and 73%, respectively.
- Green buildings' air relative humidity value was about 4.62% higher than that of conventional buildings due to the evapotranspiration of plants.
- The total energy consumption in the selected building was reduced by 10.5%, while the district cooling was reduced by 13% for the selected vegetation thickness.

Even though the initial investment outlay and regular maintenance cost of the green infrastructure are on the higher side, the socioeconomic benefits need to be taken into consideration in addition to the energy savings to better understand the contribution of greening initiatives and to quantify sustainability. The selection of drought-resistant plant species is vital to minimize maintenance costs. The impact of adding other passive technologies with green envelopes can pave the way for more rewarding cost, carbon, and energy payback benefits. Green building materials and infrastructure research involve a multidisciplinary approach.

The biological, climatic, scientific, managerial, and economic aspects of green buildings must all be explored for effective thermal management and sustainability. Several other benefits coexist with buildings integrated with green envelopes, such as good visual (aesthetic) effects and improved mental health, productivity, and quality of living, which are subjective and could be studied further. Green roofs and walls can provide significant energy and climate benefits to building owners and communities, particularly in underserved areas. Designers and other green roof professionals may help building owners and investors to reduce energy consumption by studying the factors contributing to improved performance. At the same time, a complete strategy for supporting and motivating green roofs may offer community-scale benefits such as decreased UHI and even global-scale benefits such as carbon sequestration and reduced emissions.

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