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Impact of Green Roof Plants on Building Annual Energy Consumption in a Warm Humid Climate

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Abstract

Several factors contribute to the pressing need for energy conservation in the Indian building sector. The majority of buildings still rely on conventional energy sources, leading to primarily carbon emissions. There is an increasing emphasis on promoting energy-efficient building practices and adopting green building initiatives. Green roofs, recognized as a passive energy-saving technology, exert a profound influence on the internal and external environments of buildings and cities. These ecological rooftops are the integration of vegetation, with a particular focus on identifying plant species that optimize energy and financial efficiency in the warm and humid climate of Tamil Nadu, a southern part of India. This research emphasizes the critical role of plant selection, considering parameters such as leaf area index, reflectivity, emissivity, stomatal resistance, plant height, and volumetric moisture content, encompassing initial, minimum, and maximum values. Employing advanced Design builder software, the study models the green roof of a typical 3-storey building with a 150 m2 ground surface area, examining its impact on energy consumption. The chosen plant species, Ixora coccinea, Bougainvillea, and Tabernaemontana divaricate, undergo rigorous analysis to gauge their suitability. Among these, Bougainvillea emerges as the most energy-efficient, reducing the green roof's cooling energy consumption to 16,730 kWh/year—significantly lower than the selected alternatives. This research contributes to the understanding of plant-related variables in green roof design and underscores the practical implications of selecting appropriate vegetation for enhanced sustainability in warm, humid climates, offering insights valuable for architects, urban planners, and policymakers.

Keywords: Green roof, Energy consumption, Design builder, Plants, Energy building simulation.

Introduction

Building energy consumption in India continues to rise, fueled by rapid urbanization, industrialization, and an increasing demand for infrastructure (1). The country's construction boom has led to a surge in the number of residential, commercial, and industrial buildings, contributing significantly to the escalating energy requirements (2). The demand for electricity and other energy sources in buildings is projected to intensify further in the coming years, presenting a considerable challenge in terms of energy sustainability and environmental impact (3, 4). The green building concept is one of the alternatives to minimize the building energy requirements and mitigate carbon emissions (5, 6).

Landing vegetation on a rooftop is known as "green roof technology." Green roofs are well-established in many regions of the world (7, 8). Green roofs offer several advantages, including a decreased temperature of the roof surface and surrounding air, air pollution, noise reduction, improved runoff water management, increased urban biodiversity, and decreased energy consumption of buildings, particularly for cooling purposes (9, 10). The primary goal of green roofs is to lower the overall occurrences of direct and diffuse radiation on the rooftops. In addition to offering insulation for energy savings, green roofs help reduce the temperature swings the roof membrane experiences (11-14). The roof membrane's lifespan is extended and the roof membrane's thermal stress and heat ageing are decreased (15, 16). The relative humidity is also impacted by adding vegetation to building rooftops. Green roof technology provides many advantages, including improved air quality, habitat formation on green roofs, reduced heat island effects, and decreased annual energy consumption for buildings (17-19).

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Additionally, green envelopes improve thermal comfort for building inhabitants, particularly in regions with hot, sunny days and high temperatures (20-22). The lowered cost of maintaining the indoor environment is related to the energy savings realized by deploying green roofs (23-25). Some of the most significant aspects that affect a green roof's efficiency include the type of plants grown on the surface, the soil's properties and moisture level, the leaf area index (LAI), and the leaf emissivity (26, 27) A typical green roof is a growing medium covered with vegetation and constructed using one of three key designs: intensive, semi-intensive, and extensive. The vegetation layer that makes up each of these sorts of designs differs. Tall trees are a component of intense green roofs, ground cover plants are a component of extensive green roofs and tall herbaceous plants and ground cover plants are a component of semi-intensive green roofs (28, 29). The extensive green roofs, which are the subject of the study and are appropriate for large flat roof structures and apartments, incorporate ground cover plants and a lightweight growth medium (30-32). Few studies on incorporating thermal energy storage materials in building envelopes to provide thermal management of buildings (33-35). As a result, less CO_2 emissions and energy losses increase the thermal comfort inside the building.

From the literature, by obstructing direct sunlight from reaching the roof surface, the plants grown on the rooftop have a good effect on indoor and nearby outdoor air quality. A green roof lessens thermal alterations on the roof's outside surface. It boosts the roof's heat resistance and heat capacity, keeping the interior space warmer in the winter and cooler in the summer. The study about type of plantation is not much studied in the literature. The study's major objective is to apply green roofing to a three-story building utilizing native plants. By using three vegetation models for this sort of roof were simulated for this study's modeling using the Design Builder software.

Methodology

Assessment methods of building energy

Assessing the impact of green roof plants on building annual energy consumption in a warm humid climate requires a comprehensive approach that considers various factors. Some commonly used assessment methods are as follows.

Energy monitoring can be done by installing energy monitoring equipment to measure and analyze the actual energy consumption of the building over an extended period. This provides accurate data for before and after the implementation of green roof plants. Thermal performance modeling uses building energy simulation models (e.g., EnergyPlus, eQUEST, Design Builder) to simulate the thermal performance of the building with and without green roof plants. This allows for the evaluation of energy savings under different scenarios. Meteorological data analysis analyzes local meteorological data to understand the climate conditions, including temperature, humidity, and solar radiation. This information helps in contextualizing the energy consumption patterns and assessing the impact of green roof plants. Green roof and building envelope characteristics are used to document and analyze the specific characteristics of the green roof, such as the type of plants, soil depth, and coverage. These factors influence the thermal and insulation properties of the green roof (36-38). The building envelope properties, such as insulation levels, roofing materials, and overall design can benefit by assessing how green roof plants contribute to the insulation and cooling of the building. A cooling load analysis will be used to quantify the reduction in cooling demands attributed to the shading and evaporative cooling effects of green roof plants.

Problem definition and building energy modelling

The problem identified firstly, it's imperative to rebuild the urban green spaces that were devastated and secondly, the usage of nonrenewable energy declines. The study is done on a three-story building with 150 m^2 as ground surface area. Figure 1 shows the research methodology.

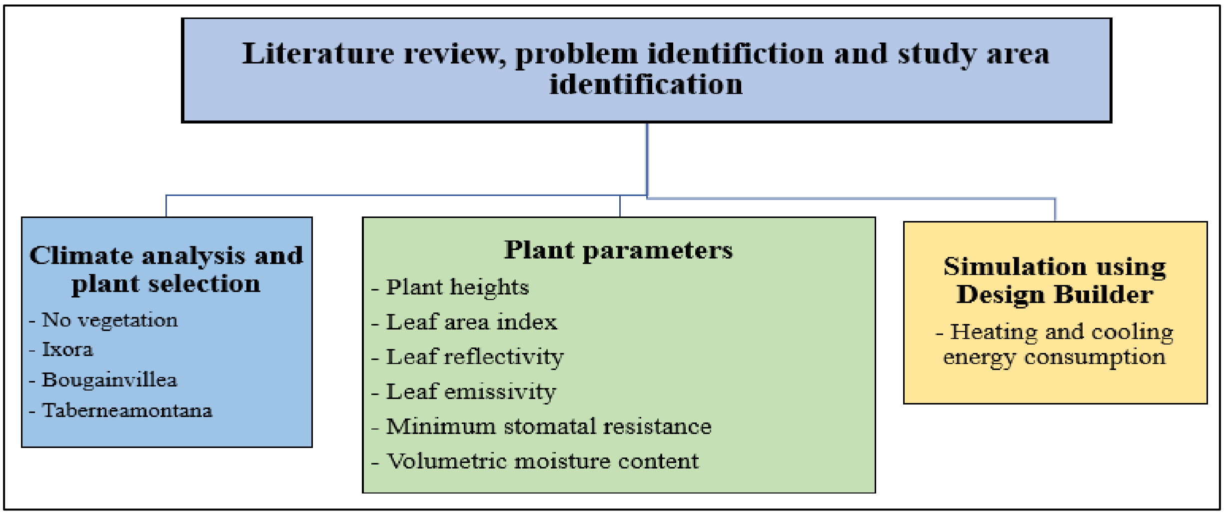

Figure 1: The research methodology adapted

Area of study

One of the 38 districts in the northeast of the Indian state of Tamil Nadu is Kanchipuram. It is one of India's greatest educational, economic, social, and cultural hubs and is renowned for its historical sites, legacy from the Pallava era, and ties to early global trade. The location of the site Potheri in the Kanchipuram district is 12.82 latitude and 80.02 longitudes. Based on India's climate zone, Kanchipuram's climate is warm and humid, with little difference in temperature between summer and winter. The summers have a lot more rain than the winters do. About 60% of the total annual rainfall is contributed by the North East monsoon, which occurs from October to December. The second one is the southwest monsoon, contributing roughly 20% of the total annual rainfall (June to September). By Koppen and Geiger, this location is categorised as Aw. Potheri's yearly mean temperature is 27.8 °C. There was an annual rain precipitation of 995 mm.

Green roof plant selection according to climate

Six types of plants that grow in warm, humid climates are identified in Table 1. The chosen plants were all ground cover kinds because this study focuses on extensive green roofs. The properties of these plants, such as their need for water, exposure to sunshine, maintenance and cost, were investigated. The selected plants are *Ixora coccinea, Bougainvillea and Tabernaemontana divaricate* based on low cost, maintenance and high photosynthesis rate.

Sunlight and Water requirement

When choosing plants for green roofing in locations with heavy sunlight, tolerance to direct sunlight is the most important factor. Shade-loving plants can tolerate some shade but cannot resist intense sunshine, making them unsuitable for green roofing in certain situations. Green roofs must utilize less water-intensive plants or, ideally, don't require watering because water scarcity issues are becoming more common worldwide. It should be highlighted that green roofs are far more challenging to water and manage than ground-level green areas. This is important to keep in mind while discussing the irrigation and upkeep of green roofs (39, 40). Table 1 shows the selected plants based on no maintenance and drought tolerance. *Phylox subulate, Hydrangea anomala and Galium odaratum* were not considered because of regular watering and sensitivity to direct sunlight.

Table 1: Ground cover plants usable in green roofs

Plant type	Sunlight requirement	Water requirement	Maintenance
Bougainvillea	full	Drought tolerance	Minimal
Ixora coccinea	Partly shade to full	Drought tolerance	Minimal
Tabernaemontana divaricate	full	Drought tolerance	Minimal

Roof structure

This building's roof was expected to be flat and comprise four layers which are shown in Fig. 2; (i) 0.15 m green roof, (ii) 0.02 m thick waterproofing layer, (iii) 0.30 m thick glass wool layer, (iv) 0.015 m thick structural support (plasterboard). The values were compared and taken from the literature reviews.

Building energy modelling

The energy modeling was developed using the Design Builder software in which a 3-storey building is constructed with the ground surface area of 150 m^2 with various layers of green roof. The chosen plants for green roof, *Ixora coccinea, Bougainvillea and Tabernaemontana divaricate* characteristics and parameters such as LAI, leaf reflectivity, plant height, leaf emissivity, leaf stomatal resistance, minimum volumetric moisture content, maximum volumetric moisture content and initial volumetric moisture content were selected from literature papers which is shown in Table 2, taking the values and incorporating them in Design Builder to find the final output of energy consumption in the building. Further, other parameters such as climate, building characteristics, and occupancy patterns are also influencing the overall energy consumption of the building.

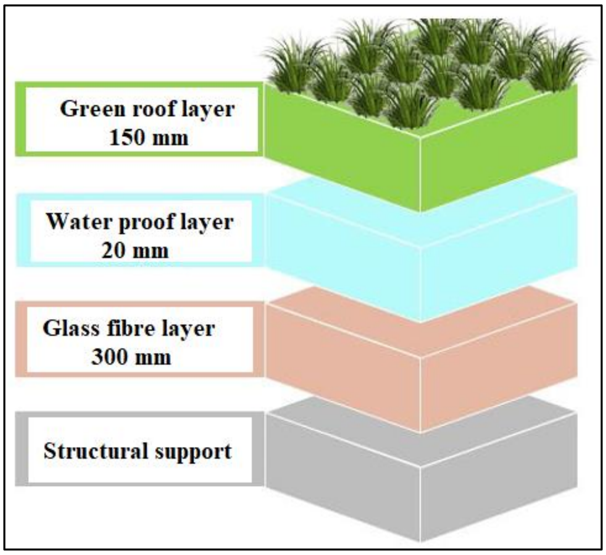

Figure 2: Composition of the green roof layer

Table 2: Parameter settings used in Design builder

Parameters	*Bougainvillea*	*Ixora coccinea*	*Tabernaemontana*
Height of plants	1	1	0.9
LAI	4.41	3.25	3.75
Leaf reflectivity	0.3	0.35	0.15
Leaf emissivity	0.95	0.80	0.85
Minimum stomatal resistance	150	250	300
The initial volumetric moisture content of the soil	0.150	0.200	0.150
The maximum volumetric moisture content of the soil (saturation)	0.500	0.500	0.500
The minimum volumetric moisture content of the soil (residual)	0.100	0.100	0.100

Results

In Figure 3, the comprehensive results of the green roof's energy consumption are visually presented, offering insights into the impact of vegetation on overall energy usage. Moving beyond a mere numerical representation, Figure 4 vividly illustrates the substantial difference in energy consumption between green roofs with vegetation and those without. Notably, a green roof devoid of any plantation is observed to be significantly more energy-intensive, registering a consumption of 46,110 kWh/year. This stark contrast underscores the pivotal role that vegetation plays in curbing the energy demands of buildings and emphasizes the transformative potential of green roof technologies.

Upon closer examination of specific plant species, the study reveals some variations. For instance, in a 3-storey building with a ground surface area of 150 m², a green roof adorned with *Ixora coccinea* is identified to have a distinct energy consumption pattern. Although this particular vegetation choice results in increased energy usage, an understanding emerges when considering the context of the overall energy landscape. Despite the elevated energy consumption, the benefits of *Ixora coccinea* become evident as it reduces energy consumption by 17,142 kWh/year. This interplay is further exemplified by the energy-saving outcomes associated with other plant species, with *Bougainvillea* contributing a reduction of 16,730 kWh/year and *Tabernaemontana* showcasing a decrease of 17,025 kWh/year. These findings not only underscore the efficacy of green roofs in mitigating energy consumption but also emphasize the importance of strategic plant selection in optimizing these energy-saving benefits. As navigating the complexities of sustainable building practices, these insights pave the way for informed decision-making in architectural and environmental planning, steering towards a more energy-efficient and ecologically responsible future. Table 3 shows major findings.

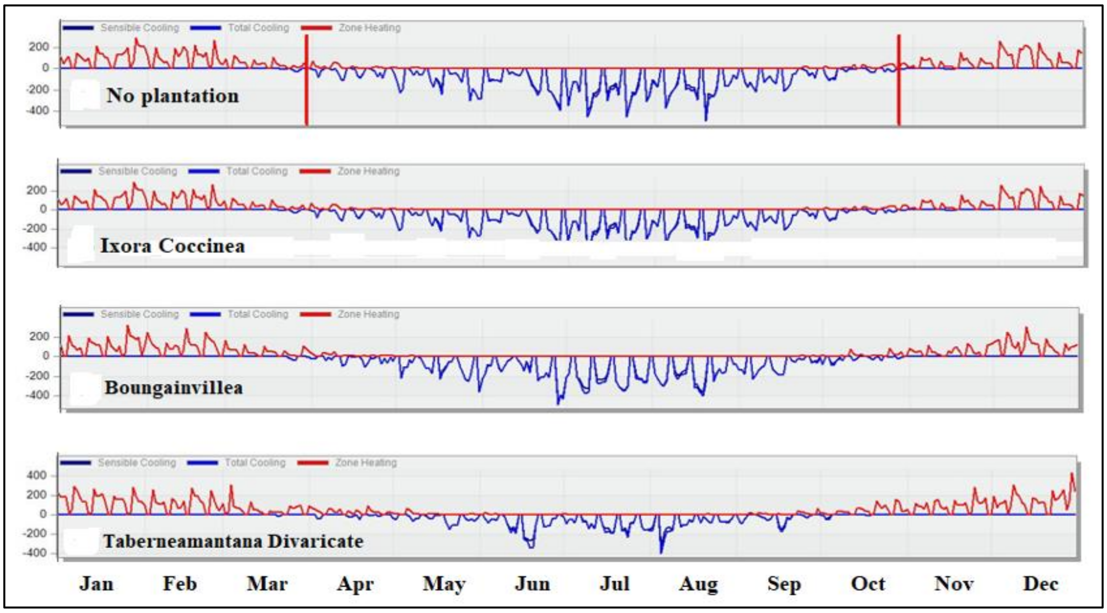

Figure 3: Energy consumption on a flat roof with and without a plantation

Table 3: Energy load comparison of roof with plantation and without plantation

Type of plantation	Cooling load (kWh/year)	Heating load (kWh/year)	Total energy demand (kWh/year)
Boungainvillea	16,730	20,111	32,625
Ixora Coccinea	17,142	20,234	33,256
Taberneamontana	17,025	21,004	35,742
Without Plantation	27,114	23,109	49,456

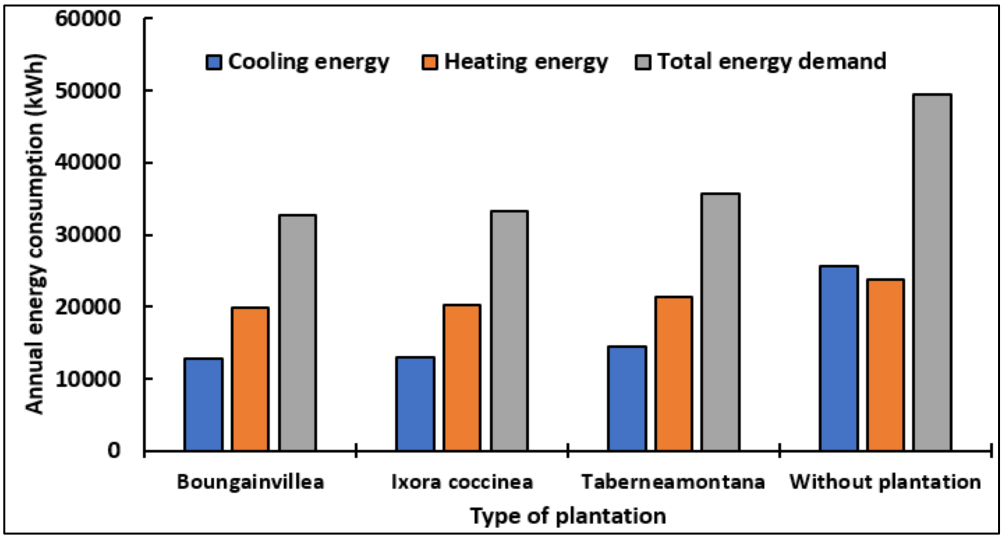

Figure 4: Energy consumption estimation

Discussion and Conclusion

The findings of the current study highlight substantial annual energy-saving potentials associated with the chosen plant species, emphasizing their significance in the context of sustainable architecture. However, it is imperative to acknowledge the dynamic nature of environmental conditions influenced by both seasonal variations and geographic factors. These variables introduce a layer of complexity in determining the ideal plant selection for specific architectural premises. Seasonal changes, such as temperature fluctuations and sunlight availability, can significantly impact the performance of green roofs, necessitating a comprehensive assessment of plant adaptability across different climatic conditions. To refine and finalize plant selection, further in-depth investigations are warranted. These studies should delve into the intricacies of mixed plantations, exploring the synergies and potential conflicts among different species. Understanding how various plants interact within the ecosystem of a green roof is essential for optimizing energy efficiency and overall ecological benefits. Moreover, the effects of mixed plantations on environmental air quality represent a crucial aspect that demands thorough examination. Investigating the plants' collective influence on air purification, oxygen release, and pollutant absorption will contribute valuable insights towards establishing a holistic understanding of green roofs' environmental impacts.

In addition to plant selection, the determination of optimal plantation height and other characteristics requires careful consideration. Examining the interplay between plant height, architectural features, and energy consumption patterns is vital for maximizing the benefits of green roofs. This holistic approach ensures that green roof designs not only contribute significantly to energy conservation but also align seamlessly with the broader goals of enhancing environmental sustainability and urban resilience (38-40). As such, future research endeavors should encompass a multifaceted exploration of plant combinations, environmental outcomes, and design parameters to establish comprehensive guidelines for the implementation of green roofs in diverse architectural settings.

Green roofs offer a desirable solution for reducing building energy consumption and enhancing the environmental health of cities. This work investigated the impacts of three plantation layers as green roofs on a building's energy efficiency. Three plants were ultimately chosen as the best plants: *Ixora coccinea, Bougainvillea and Tabernaemontana divaricate*. Six ground cover plants can be employed in substantial green roofs.

- The alternatives were then reduced by removing unsuitable plants for the research area's warm and humid climate in terms of maintenance, sunlight, and water requirements. Finally, estimates and comparisons of the green roofs with these plants' energy-saving capabilities were made.

- For the selected study area, *Bougainvillea* is the best-suited plant with the least cooling load of 16,730 kWh/year and the total energy demand of 32,625 kWh/year when compared to the other two plants.
- For the selected study area, roof without plantation consumes cooling load of 27,114 kWh/year and the total energy demand of 49,456 kWh/year when compared to roof with plantation.
- From the above Table 3, Roof with *Boungainvillea* reduces the total energy demand upto 52% (16,831 kWh/year) when compared to roof without plantation.

The present study shows immense annual energy-saving potentials with the selected plants. The influence of seasonal and geographic factors is to be closely observed to finalize the plant selection for the particular architectural premises. Further studies are required to determine the mixed plantations and the overall effects on environmental air quality to finalize the optimal plantation height and other characteristics. By combining several assessment methods, researchers and practitioners can obtain a comprehensive understanding of the impact of green roof plants on building annual energy consumption in a warm humid climate. This multidimensional approach helps account for various factors that may influence the results and supports informed decision-making in sustainable building design.

Abbreviation

LAI: Leaf area index

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Author contributions

Jenny Sharon: Conceptualization, Methodology, Formal analysis, Investigatiuon, Writing -Original draft, Radhakrishnan Shanthi Priya: Conceptualization, Methodology, Investigatiuon, Writing-Original draft, Prashanthini Rajagopa: Methodology, Investigation, Writing-Original draft, Chandramouli Pradeepa: Formal analysis, Validation, Writing–review & editing. Ramalingam Senthil: Methodology, Validation, Writing–review & editing.

Conflict of interest

The authors declare that there is no conflict of interest.

Ethics approval

Not applicable

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