

Comparative Performance Analysis of Eco-Friendly and Conventional Buildings in Terms of Energy and Environmental Efficiency

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Abstract- Eco-friendly buildings are designed to minimize environmental impact while enhancing resource efficiency and occupant well-being throughout the building life cycle. Compared to conventional buildings, such structures consume less energy and water, utilize sustainable materials, generate reduced waste, and provide improved indoor environmental quality. With the rapid expansion of the green construction market, it has become essential to critically evaluate whether eco-friendly buildings offer measurable performance advantages over conventional residential buildings. This study presents a comparative analysis of eco-friendly and conventional residential buildings with respect to energy performance, water consumption, waste management, and indoor environmental conditions. Temperature distribution and thermal behavior were analyzed using Energy2D simulation software to assess the effectiveness of passive design strategies in reducing cooling demand. Data related to electricity usage, water consumption, and waste generation were collected and evaluated using established green building assessment frameworks, including the Leadership in Energy and Environmental Design (LEED) rating system. The eco-friendly building model incorporated integrated sustainability features such as rainwater harvesting systems, greywater treatment units, biogas plants, cooling tunnels, and passive solar control measures. The results indicate that eco-friendly buildings demonstrate significantly lower operational energy demand, improved water efficiency, and enhanced indoor air quality compared to conventional buildings. In the context of increasing concerns related to global climate change and rising greenhouse gas emissions, the findings highlight the critical role of sustainable building practices in reducing energy consumption and environmental degradation. The study confirms that eco-friendly buildings offer tangible technological, environmental, and operational benefits, supporting their adoption as a viable and effective alternative to conventional building practices.

Keywords - Eco-friendly building, Conventional building, Energy efficiency ,Sustainable construction, Green building rating systems, Indoor environmental quality.

I. INTRODUCTION

India is experiencing rapid economic growth driven by industrialization, population expansion, and large-scale infrastructure development. While these factors contribute to national progress, they simultaneously exert significant pressure on natural resources and the built environment. The construction sector, in particular, is a major consumer of energy, water, and raw materials, and is a substantial contributor to greenhouse gas emissions and environmental degradation. In this context, eco-friendly buildings have

emerged as a viable solution to mitigate the adverse environmental impacts associated with conventional construction practices. An eco-friendly building is defined as a structure that is environmentally responsible and resource-efficient throughout its entire life cycle, including planning, design, construction, operation, maintenance, and end-of-life disposal. Such buildings emphasize sustainability, high operational performance, and improved indoor environmental quality. Compared to conventional buildings, eco-friendly buildings are designed to reduce energy consumption, optimize water use, minimize waste generation, and enhance occupant health and comfort. Thermal comfort is a critical aspect of building performance, particularly in tropical and composite climatic regions such as Pune, India. Traditional residential buildings in this region historically relied on passive design strategies, including natural ventilation, shading, thermal mass, and orientation, to achieve acceptable indoor comfort conditions. However, modern buildings often neglect these principles and instead depend heavily on energy-intensive mechanical cooling systems. This over-reliance has resulted in increased energy demand, higher operational costs, occupant discomfort, and, in some cases, adverse health and productivity outcomes. In addition to energy concerns, water scarcity has become a pressing global issue. Although water covers a significant portion of the Earth's surface, the availability of potable water is increasingly limited in densely populated regions. Inefficient water use, inadequate wastewater treatment, and improper solid waste management further exacerbate environmental and public health risks. Unmanaged organic and plastic waste contributes to pollution, greenhouse gas emissions, and the spread of infectious diseases. Eco-friendly buildings address these challenges through integrated strategies such as renewable energy utilization, rainwater harvesting, greywater recycling, efficient waste management systems, and the use of sustainable construction materials. By incorporating passive and active technologies, eco-friendly buildings offer a comprehensive approach to reducing environmental impact while promoting human health and long-term sustainability. Consequently, evaluating the performance of eco-friendly buildings in comparison with conventional buildings is essential to support evidence-based adoption of sustainable construction practices.

Motivation

This study is motivated by the need to quantitatively compare the performance of eco-friendly and conventional residential buildings. Energy2D simulations and operational data on energy, water, and waste are used alongside LEED criteria to evaluate the effectiveness of sustainable design strategies and eco-friendly building systems.

II. LITERATURE REVIEW

Avinash Shivajirao Pawar (2021) examined the design principles of eco-friendly buildings with the objective of reducing dependence on non-renewable resources while maximizing reuse and recycling of materials. The study defined eco-friendly buildings as structures that enhance resource efficiency and minimize adverse impacts on human health and the environment. The author highlighted that eco-friendly building practices in India present both opportunities and challenges, yet they play a critical role in conserving energy and natural resources through sustainable material use and waste recycling [1].

Sunita Bansal, S. K. Singh, and Srijit Biswas (2022) conducted a detailed case study in Delhi focusing on performance improvement strategies for existing buildings. Their work involved comprehensive audits, including water audits to identify excessive consumption, waste audits to quantify recycling and disposal practices, and condition audits to assess the remaining service life of building components. Thermal audits covering indoor comfort, air quality, lighting, and noise levels were also performed, revealing significant scope for performance enhancement through targeted interventions [2].

Tandel and Patel (2021) explored energy-efficient solutions for futuristic buildings, emphasizing the role of advanced technologies and building information modeling (BIM) in improving building performance and sustainability ratings. Their study highlighted that optimized daylighting strategies, energy-efficient lighting systems, and accurate building energy simulation tools can significantly reduce energy

consumption. The authors also demonstrated that advanced simulation tools, supported by artificial intelligence techniques, achieved high accuracy in predicting heating and cooling energy demand [3].

Kim (2021) compared contemporary architectural practices in Korea with traditional building systems, focusing on their ability to regulate indoor climate. The study concluded that modern buildings often rely heavily on energy-intensive mechanical systems, leading to ecological challenges, whereas traditional designs demonstrated superior climate responsiveness through passive strategies. The research emphasized the need to reintroduce environmentally self-sustaining design principles in modern architecture [4].

Zuo and Zhao (2021) reviewed sustainable construction technologies and examined their current applications and future potential. Their analysis revealed that existing research predominantly concentrates on the environmental dimensions of sustainable buildings, while economic and social aspects receive comparatively less attention. The study underscored the importance of comprehensive evaluation frameworks for assessing the benefits of sustainable buildings over conventional structures [5].

Engin et al. (2022) investigated the influence of climatic conditions on vernacular residential architecture in the Eastern Black Sea region. Their findings demonstrated that local climate factors such as rainfall, humidity, and solar exposure significantly influence building layout, envelope design, roofing systems, and material selection, reinforcing the importance of climate-responsive architectural design [6].

Turker and Dincyurek (2021) analyzed traditional residential patterns within a historical island context, exploring their relevance for contemporary housing design. The study emphasized the preservation of local architectural identity while adapting traditional design principles to meet modern environmental and functional requirements, highlighting the role of place-based design in sustainable development [7].

III. PROBLEM STATEMENT

Despite the long-term environmental and economic benefits of eco-friendly buildings, their widespread adoption remains limited, primarily due to perceived high initial investment costs and design complexity. Although operational savings over time can offset the initial expenditure, the upfront cost continues to be a major barrier for developers and homeowners. Additionally, inadequate design integration often leads to challenges in maintaining indoor thermal comfort, particularly in hot and composite climatic regions. In some cases, eco-friendly buildings are incorrectly perceived as unsuitable for such climates due to improper application of passive ventilation strategies and overreliance on centralized systems. These issues can compromise indoor comfort and undermine the intended sustainability objectives.

The absence of performance-based comparative studies further complicates decision-making, as stakeholders lack clear quantitative evidence demonstrating the advantages of eco-friendly buildings over conventional buildings. Addressing these challenges requires systematic evaluation of building performance using reliable simulation tools, operational data, and standardized assessment frameworks.

Objectives of the Study

The objectives of this study are as follows:

- To analyze the energy consumption characteristics of an existing residential building.
- To assess the building's environmental performance using recognized eco-friendly building assessment tools.
- To identify and implement appropriate strategies for transforming a conventional residential building into an eco-friendly building.
- To perform a comparative evaluation of conventional and eco-friendly residential buildings in terms of passive design strategies, material usage, energy performance, water efficiency, and simulation-based thermal behavior.

The overall objective of the study is to demonstrate how eco-friendly building strategies can reduce resource consumption, enhance energy efficiency, minimize waste generation, conserve natural resources, and provide healthier indoor environments for occupants.

IV. Methodology

The aim of this study is to quantitatively evaluate the performance of eco-friendly and conventional residential buildings and to assess the effectiveness of sustainable design strategies in energy, water, and waste management. The research adopts a case-study-based approach, combining simulation, field measurements, and standardized rating tools to provide an integrated evaluation.

Methodological Framework

The research methodology is divided into four sequential stages, as outlined in **Table 1**:

Table 1: Stages of Research Methodology

Stage	Description	Methods / Tools
1. Problem Identification	Identify issues in conventional construction; define research objectives and scope	Literature review, site selection
2. Literature Survey	Review of eco-friendly building concepts, rating systems, materials, and technologies	Academic journals, rating manuals (LEED, GRIHA, BREEAM), case studies
3. Data Collection and Case Study Preparation	Selection of building; measurement of energy, water, and waste usage; building envelope and materials assessment	Energy2D simulation, field measurements, interviews with occupants, building documentation analysis
4. Analysis and Evaluation	Comparative analysis between conventional and eco-friendly building; performance evaluation using rating systems	LEED/GRIHA assessment, energy & water usage calculations, thermal comfort analysis, statistical evaluation

Simulation and Measurement Tools

- **Energy Simulation:** Energy2D software is used to model temperature distribution and evaluate thermal comfort in selected buildings. Simulations consider seasonal variations and passive cooling strategies.
- **Water and Waste Assessment:** Daily water consumption, greywater recycling, and waste generation are recorded and analyzed.
- **Rating System Evaluation:** The LEED and GRIHA frameworks are applied to assess the sustainability performance of the building in terms of energy efficiency, water efficiency, materials, indoor environmental quality, and renewable energy integration.

Case Study Selection

The study focuses on a residential building in Pune, Maharashtra, selected based on the following criteria:

1. Compliance with eco-friendly construction features (passive design, energy-efficient systems, water and waste management).
2. Similar climatic and environmental conditions to allow comparison with conventional buildings.
3. Availability of operational data for energy, water, and waste consumption.

Data Collection Procedures

Data collection includes both primary and secondary sources:

- Primary Data: Field measurements of energy consumption, water use, waste generation, and indoor temperature profiles.
- Secondary Data: Literature review on eco-friendly materials, construction techniques, and previous case studies for benchmarking purposes.

Data from simulations and field measurements are integrated to provide a comprehensive understanding of the building's environmental performance.

Comparative Analysis

The performance of the selected eco-friendly building is compared with a conventional building using the following metrics:

1. Energy Consumption (kWh/year)
2. Water Usage (L/year)
3. Waste Generation (kg/year)
4. Indoor Thermal Comfort (temperature and humidity ranges)
5. LEED / GRIHA Rating Scores

This comparison allows quantification of the benefits of eco-friendly design strategies and highlights the contribution of passive and active sustainability measures.

V. CASE STUDY

Case Study the Pimpri Chinchwad New Town Development Authority (PCNTDA)

The selected case study is the Administrative Building of the Pimpri Chinchwad New Town Development Authority (PCNTDA), located at Akurdi in Pune District, Maharashtra, India (18°64'94" N, 73°76'89" E). The building is situated in Pimpri-Chinchwad, a rapidly developing twin city of Pune, and serves as the primary administrative facility for the regional development authority. The building is a seven-storey mid-rise commercial structure designed to accommodate office spaces, meeting rooms, and conference facilities. The total site area is 20,344 sqm, with a built-up area of 10,835 sqm. Of this, only 607 sqm is air-conditioned, while the remaining 10,228 sqm operates under non-air-conditioned conditions, emphasizing the reliance on passive design strategies. The building functions for approximately eight hours per day. Pune is classified under the warm and humid climatic zone according to the Energy Conservation Building Code (ECBC); however, it experiences a relatively moderate climate for most of the year. A significant climatic characteristic influencing the design is the prevailing westerly wind, which originates from the Arabian Sea and travels inland across the Western Ghats, resulting in cooler and less humid airflow. These conditions were utilized to enhance natural ventilation and thermal comfort.

The building form and orientation were developed by integrating functional requirements with solar passive design principles. Located at approximately 18.5° north latitude, the site allows north-facing orientations to provide optimal daylight with minimal solar heat gain. Accordingly, the design consists of two narrow blocks, approximately 14 m wide, oriented towards the north-northeast and rising to nearly 30 m in height. The blocks are staggered to ensure unobstructed daylight penetration and visual connectivity. Triangular plan spaces house vertical circulation elements, including staircases, lifts, and service cores. To enhance cross-ventilation, the narrow eastern and western façades are sculpted in alignment with prevailing wind directions. Fenestration is designed as an integral architectural element, with orientation-specific shading devices such as overhangs to control solar radiation.

High-performance double-glazed windows are employed to reduce heat gain while maintaining adequate daylight levels. External walls are constructed using fly ash blocks, incorporating recycled materials and reducing embodied energy. The building demonstrates significant improvements in energy and water performance compared to GRIHA benchmarks. An Energy Performance Index (EPI) of 17 kWh/sqm/year has been achieved, corresponding to a 46% reduction in energy consumption. A 100 kWp rooftop solar photovoltaic system has been installed to meet a portion of the on-site energy demand. Water efficiency measures include rainwater harvesting, low-flow plumbing fixtures, and an on-site sewage treatment plant (STP). More than 50% of the annual water demand is met through rainwater harvesting, while treated wastewater is reused for landscaping, resulting in a 71% reduction in water consumption. Over 60% of the building spaces are adequately daylight, and energy-efficient lighting systems comprising LEDs and tubular fluorescent lamps further reduce electrical loads. Additionally, more than 60% of the interior finishes utilize low-energy materials. Owing to the integration of climate-responsive planning, passive architectural strategies, and efficient building systems, the PCNTDA Administrative Building has achieved a 5-Star rating under the GRIHA green building rating system.



Figure 1- View of PCNTDA

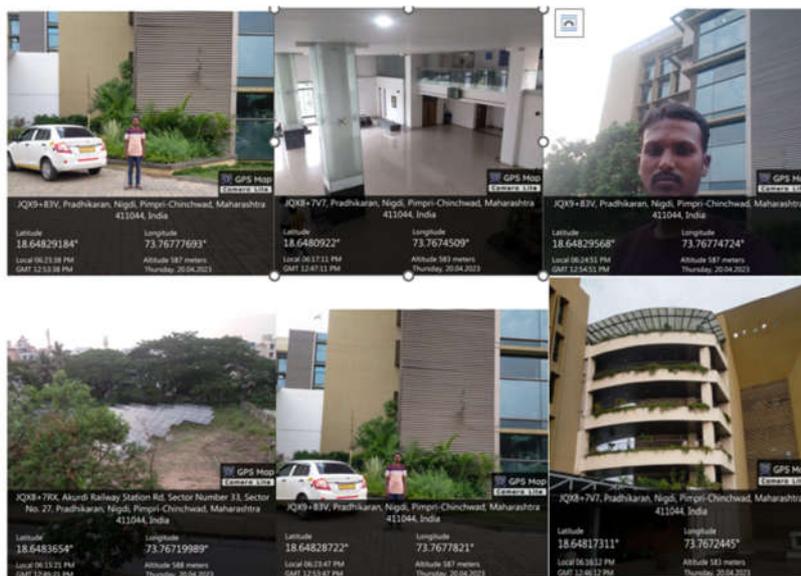


Figure 2- PCNTDA Visit Photographs

Case Study: Royal Orange County, Pune, India

Royal Orange County is an eco-friendly residential development located in Pune, Maharashtra, within the rapidly urbanizing Pune–Pimpri Chinchwad region. The project represents a growing trend toward sustainable residential development in the region, aligning with the objectives of the Green Rating for Integrated Habitat Assessment (GRIHA) system. The Pune and Pimpri Chinchwad region has emerged as a leading hub for the adoption of GRIHA-rated green buildings. GRIHA is India’s national rating system for evaluating the environmental performance of buildings and habitats against established benchmarks. The system emphasizes the reduction of carbon footprint, optimization of energy and water consumption, integration of renewable energy systems, and enhancement of indoor environmental quality to provide thermal and visual comfort to occupants. Buildings designed in accordance with GRIHA principles typically achieve a reduction of approximately 30–40% in operational costs over conventional developments.

Formulated by the GRIHA Council—an independent, not-for-profit organization established by The Energy and Resources Institute (TERI) in collaboration with the Ministry of New and Renewable Energy (MNRE), Government of India—the rating system evaluates projects across their entire life cycle. This includes the design phase, construction stage, and operational performance, thereby encouraging a holistic approach to sustainable development. Royal Orange County incorporates sustainability strategies consistent with GRIHA objectives, focusing on resource efficiency and environmentally responsible planning. The project adopts energy- and water-conservation measures, renewable energy integration, and design strategies that enhance indoor comfort while minimizing environmental impact. Such measures contribute to reduced dependence on conventional energy sources and improved long-term building performance. The widespread adoption of GRIHA-certified buildings in Pune has been further encouraged through policy-level incentives offered by local authorities. The Pimpri Chinchwad Municipal Corporation (PCMC) provides premium charge rebates ranging from 10% to 50% for developers of GRIHA- and SVA-GRIHA-certified buildings, depending on the achieved star rating (1–5 stars). Additionally, property owners benefit from tax rebates, with reductions of 5–10% for 3–5 Star GRIHA-certified buildings and 5–15% for SVA-GRIHA-rated developments. These incentives have played a significant role in promoting environmentally sustainable residential projects such as Royal Orange County. The case of Royal Orange County demonstrates how policy support, rating frameworks, and environmentally responsive design can collectively facilitate the development of sustainable residential habitats in rapidly growing urban regions such as Pune.

VI. RESULT AND DISCUSSION

The comprehensive study of the Administrative Building of the Pimpri Chinchwad New Town Development Authority (PCNTDA) demonstrates the successful realization of a high-performance, eco-friendly institutional building through climate-responsive and passive design strategies. The building serves as a model green building that establishes a strong pro-environmental statement by minimizing dependence on mechanical systems while maximizing the use of natural resources. Given Pune’s predominantly moderate climate, with extreme summer conditions limited to approximately four months, the design intent focused on maximizing naturally ventilated and passively cooled spaces while minimizing artificially conditioned areas. Building orientation played a critical role, with the longer façades aligned along the north–south axis to reduce solar heat gain. Maximum glazing was provided on the north façade to harness diffused daylight, thereby minimizing glare and heat ingress. A combination of horizontal and vertical shading devices was employed to control direct solar radiation. Additional passive strategies included the

use of light shelves for deeper daylight penetration, evaporative cooling through strategically placed water bodies, and a ventilated roof undersurface to dissipate accumulated heat.

As a result of these measures, artificial air-conditioning was limited to only 11,237 sq.ft. of the total carpet area of 63,072 sq.ft., leading to substantial operational energy savings. The building achieved an annual monetary saving of approximately INR 5.55 million solely through reduced air-conditioning demand. The GRIHA rating framework was adopted as a guiding tool throughout the design and construction process. In compliance with GRIHA's renewable energy requirements, a 100 kWp rooftop solar photovoltaic system was installed, supported by a 30% capital subsidy from MNRE. The installed system is capable of offsetting the building's annual electricity demand, further reducing operational costs.

Comparative Energy Performance Analysis

Air-Conditioning Energy Consumption

In a conventional office building, 100% of the carpet area is typically air-conditioned. For a comparable conventional building with a carpet area of 63,072 sq.ft., the required cooling capacity is estimated at 460 TR. The annual energy consumption for air-conditioning under an 8-hour daily operation over 270 working days amounts to approximately 1,192,320 units. In contrast, the PCNTDA building conditions only 11,237 sq.ft., with an installed cooling capacity of 82 TR. The combined daily energy consumption of air-conditioning and ceiling fans is 877.2 units, resulting in an annual consumption of 236,844 units. This yields an annual energy saving of 955,476 units. At a commercial electricity tariff of INR 5.50 per unit, the annual cost saving achieved through natural ventilation and reduced mechanical cooling is approximately INR 5,555,118.

Daylighting Energy Analysis

In a conventional office building, artificial lighting requirements are met using approximately 1,200 fluorescent fixtures, consuming an annual energy of about 260,820 units. The PCNTDA building achieves significant daylight penetration, reducing reliance on artificial lighting for a majority of working hours. Orientation-specific fenestration and shading devices enable effective daylight utilization, resulting in substantial reductions in lighting energy demand.

Comparative Material and System Performance

A comparative assessment between a conventional residential building (Dream Home, Talegaon) and a green building (Royal Orange County, Pune) highlights the advantages of sustainable materials and systems. The green building utilizes Portland Pozzolana Cement (PPC), fly ash bricks, non-VOC paints, insulated glazing, low-flow plumbing fixtures, LED lighting, rainwater harvesting systems, and rooftop solar panels. These choices result in improved durability, reduced embodied energy, enhanced indoor environmental quality, and significant reductions in energy and water consumption.

The green building demonstrates approximately 12.94% cost benefit over the conventional building when lifecycle savings are considered, despite marginally higher initial investment.

Water Efficiency and Resource Conservation

Rainwater harvesting systems in the green building enable the collection of approximately 7,920 liters per day, contributing significantly to non-potable water demand. Treated wastewater from a root-zone sewage treatment plant (STP) is reused for flushing and landscaping, resulting in a water consumption reduction of

nearly 40%. These measures collectively reduce dependence on municipal water supply and contribute to groundwater recharge.

Environmental Impact Reduction

The integration of hybrid renewable energy systems (solar and wind), solar water heating, and energy-efficient fixtures results in an annual energy saving of approximately 106,729 units. This translates into a coal consumption reduction of 55.5 tonnes per year and a corresponding CO₂ emission reduction of approximately 90 tonnes annually. These outcomes underscore the effectiveness of passive design and renewable energy integration in mitigating environmental impacts.

VII. CONCLUSION

The present study demonstrates that climate-responsive design, when integrated with passive architectural strategies and guided by an established sustainability framework such as GRIHA, can significantly enhance the environmental and operational performance of institutional and residential buildings in moderate-warm climatic regions such as Pune. The Administrative Building of the Pimpri Chinchwad New Town Development Authority (PCNTDA), along with the comparative analysis of green and conventional buildings, provides empirical evidence of the effectiveness of reducing dependence on mechanical systems through informed design decisions. The findings indicate that appropriate building orientation, optimized fenestration, and façade-specific shading devices play a crucial role in minimizing solar heat gain while maximizing daylight availability. The strategic limitation of air-conditioned spaces, supported by natural ventilation, resulted in substantial reductions in energy consumption and operational costs without compromising occupant comfort. The PCNTDA building achieved significant annual energy savings and monetary benefits, primarily through reduced cooling demand, efficient lighting systems, and extensive use of daylight. The integration of renewable energy systems, particularly rooftop solar photovoltaic installations, further contributed to lowering grid dependency and carbon emissions. Water efficiency measures, including rainwater harvesting and on-site wastewater treatment, demonstrated the potential for reducing freshwater demand and enhancing resource self-sufficiency. The observed reductions in coal consumption and CO₂ emissions highlight the role of green buildings in mitigating environmental impacts associated with rapid urbanization. Overall, the study confirms that green building practices, when evaluated across energy, water, materials, and indoor environmental quality parameters, offer measurable lifecycle benefits over conventional construction. The results emphasize the importance of adopting passive design principles as a primary strategy, with renewable energy systems acting as complementary solutions. The case studies reinforce the applicability of GRIHA as a robust tool for achieving sustainable built environments and provide valuable insights for policymakers, designers, and developers aiming to promote environmentally responsible construction in emerging urban contexts.

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