Energy-Efficient Housing Design and Its Impact on Thermal Comfort and Social Well-being in Low-Income Communities

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ABSTRACT
Rapid urbanization and rising energy demand have intensified the challenge of delivering thermally comfortable, energy-efficient housing for low-income communities in developing regions. Poor building design, unsuitable materials, and limited access to mechanical cooling or heating systems often result in severe thermal discomfort, negatively affecting health, productivity, and overall well-being. This study explores the link between energy-efficient housing design, indoor thermal conditions, and social well-being among low-income households. A mixed-method approach integrates technical and socio-behavioral analysis. Field measurements of indoor temperature and humidity are combined with assessments of building design features to evaluate thermal performance. Simultaneously, structured questionnaires and interviews capture residents' perceptions of comfort, health impacts, and adaptive behaviors. Simulation tools are further used to examine the effectiveness of passive strategies such as natural ventilation, insulation, and optimized material use in enhancing indoor conditions while reducing energy consumption. The results reveal a strong correlation between housing design and thermal comfort. Simple, low-cost design interventions significantly improve indoor environmental quality. Enhanced thermal conditions are linked to better health outcomes, lower stress levels, and increased occupant satisfaction. Additionally, socio-economic factors—such as awareness, cultural practices, and financial limitations—play a crucial role in shaping energy use patterns and comfort perception. This study highlights the importance of integrating engineering solutions with social insights to develop sustainable, inclusive housing. It offers practical guidance for policymakers, planners, and engineers to promote affordable, climate-responsive design strategies that balance energy efficiency with social equity.

Keywords: Energy-efficient housing, thermal comfort, low-income communities, indoor environmental quality, passive design, social well-being

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1. Introduction

1.1 Background and Context

Rapid urbanization and population growth have significantly increased global energy demand, placing pressure on infrastructure and resources. In developing regions, this strain is most evident in the housing sector, where affordability often takes priority over energy efficiency. As a result, many low-income households live in poorly designed structures lacking proper orientation, ventilation, and suitable materials. These deficiencies not only increase dependence on external energy sources but also create uncomfortable indoor environments, particularly during extreme climatic conditions. Rising energy costs further exacerbate these challenges, disproportionately affecting economically weaker sections.

1.2 Thermal Comfort and Its Importance

Thermal comfort is a vital yet often overlooked aspect of housing quality in low-income communities. Unlike high-income households that rely on mechanical systems such as air conditioning or heating, low-income residents depend largely on passive strategies to maintain indoor comfort. When buildings fail to support natural cooling or heating, occupants face prolonged exposure to thermal stress. This can result in health issues such as dehydration, fatigue, and respiratory problems, along with reduced productivity and mental well-being. Thus, thermal comfort is not only a technical concern but also a matter of human dignity and social welfare.

1.3 Interdisciplinary Approach

This study adopts an interdisciplinary framework combining civil engineering, mechanical engineering, and sociological perspectives. Civil engineering focuses on building design, construction methods, and material properties that influence thermal performance. Mechanical engineering contributes by examining ventilation systems, heat transfer processes, and low-cost technological solutions. Sociology provides insight into how cultural practices, economic constraints, and behavioral patterns affect how residents interact with their built environment. This integrated approach enables a comprehensive understanding of both technical and human dimensions of housing performance.

1.4 Research Gap

Despite growing attention to sustainable housing, a gap remains between engineering solutions and the realities of low-income populations. Many studies emphasize advanced technologies and high-performance materials that are not economically feasible for marginalized groups. Additionally, social factors such as occupant behavior, awareness, and adaptive strategies are often underrepresented. This disconnect limits the applicability of existing research in resource-constrained settings.

1.5 Objectives of the Study

In response to these challenges, the study aims to: (i) evaluate the role of energy-efficient design features in improving indoor thermal conditions; (ii) analyze the relationship between thermal comfort and occupants' social well-being; and (iii) identify cost-effective, context-sensitive strategies that enhance both energy efficiency and quality of life. The findings are intended to support the development of inclusive housing policies and sustainable design practices.

2. Literature Review

2.1 Energy-Efficient Building Design

Energy-efficient design has become essential in addressing rising energy demand and environmental concerns, particularly in low-income housing. Building performance is largely influenced by orientation, material properties, and passive design strategies. Research shows that poorly oriented structures with limited ventilation and shading experience excessive indoor heat, often surpassing outdoor temperatures. Materials also play a critical role: high thermal conductivity materials such as tin sheets or uninsulated concrete rapidly absorb and transfer heat, whereas insulated or locally suitable materials help maintain stable indoor conditions. Even simple design improvements—such as better ventilation, reflective roofing, and appropriate orientation—can significantly enhance thermal performance. However, adoption in low-income communities remains constrained by cost, limited awareness, and construction challenges. This variation in thermal response can be conceptually summarized as follows:

Design Feature	**Thermal Impact on Indoor Environment**
Poor ventilation	Heat accumulation, reduced air flow
Tin roofing	Rapid heat gain
Insulated roofing	Reduced heat transfer
Proper orientation	Lower solar heat gain

2.2 Thermal Comfort Theories and Models

Thermal comfort is traditionally evaluated using standardized models based on environmental variables like temperature, humidity, and airflow. While effective in controlled environments, these models often fail to reflect conditions in naturally ventilated, low-income housing. Studies indicate that comfort perception is dynamic and influenced by adaptive behaviors such as clothing adjustment and activity changes. Generally, higher indoor temperatures reduce comfort levels, while increased air movement improves it. Empirical findings consistently demonstrate a strong inverse relationship between thermal stress and occupant satisfaction, supporting adaptive comfort theories that emphasize human flexibility in responding to environmental conditions.

2.3 Mechanical Systems and Passive Design

Mechanical systems such as HVAC are designed to regulate indoor environments but are often unaffordable for low-income households due to high costs. As a result, passive design strategies are the primary means of achieving comfort. Techniques such as natural ventilation, shading, and reflective materials can reduce indoor temperatures without external energy use. Individually, these strategies provide moderate improvements, but when combined, they can significantly enhance indoor conditions. Mechanical engineering contributions focus on optimizing airflow and integrating low-energy systems, leading to hybrid solutions that balance comfort with energy efficiency. A generalized performance comparison is often observed:

Intervention Type	Expected Impact on Temperature
Natural ventilation	Moderate reduction
Shading devices	Reduced solar heat gain
Reflective surfaces	Lower heat absorption
Combined strategies	Significant improvement

2.4 Socio-Economic Aspects of Housing

Housing conditions in low-income communities are shaped by financial constraints, social practices, and cultural preferences. Limited resources often result in compromised construction quality, negatively affecting thermal performance. High occupancy levels further influence indoor conditions. Importantly, comfort perception is not purely physical; it is shaped by expectations, adaptability, and awareness. Studies show that most residents report moderate to low comfort levels, yet many adapt to suboptimal environments. Prolonged exposure to such conditions, however, can adversely impact health and well-being, highlighting the need for both technical and social interventions. A typical distribution observed in such studies is as follows:

Comfort Level	Percentage of Occupants
Low Comfort	High proportion
Moderate Comfort	Moderate proportion
High Comfort	Limited proportion

2.5 Previous Studies on Low-Income Housing

Existing research consistently identifies poor thermal performance, inadequate ventilation, and limited access to energy-efficient technologies in low-income housing. Field studies reveal that elevated indoor temperatures contribute to discomfort and health issues. Quantitative analyses show clear relationships between environmental conditions and well-being, including reduced productivity, poor sleep quality, and increased health risks. Common findings include a negative correlation between temperature and comfort, and a positive association between ventilation and occupant satisfaction. However, many studies address technical and social aspects separately, limiting comprehensive understanding.

2.6 Identified Research Gaps

The literature reveals several key gaps. First, there is a lack of integrated studies combining engineering and socio-behavioral perspectives. Second, generalized models often overlook local climatic, cultural, and economic variations, reducing their practical relevance. Third, existing analyses do not fully capture the combined influence of multiple variables such as materials, ventilation, and occupant behavior. Finally, affordability remains a major barrier, as many proposed solutions are not viable for low-income populations. Addressing these gaps requires an interdisciplinary and context-sensitive approach that integrates technical efficiency with social realities—an objective central to the present study.

3. Case Study / Study Area Analysis

3.1 Description of Selected Housing Units

The study examines low-income residential clusters in Dehradun, characterized by a mix of semi-permanent and permanent structures. Most houses are compact, typically comprising one or two rooms with limited access to ventilation and natural light. Unplanned layouts and closely spaced buildings restrict airflow and contribute to heat accumulation.

The housing units are categorized into three types based on structural characteristics:

Housing Type	Description	Average Floor Area (m²)	Occupancy (Persons)
Type A	Temporary/semi-permanent with tin roofing	18–25	4–6

Housing Type	Description	Average Floor Area (m²)	Occupancy (Persons)
Type B	Brick walls with concrete roofing	25–35	5–7
Type C	Improved design with better layout and spacing	30–45	3–5

This classification enables comparison of how structural variations influence thermal conditions and comfort levels.

3.2 Construction Materials and Techniques

Construction practices are primarily driven by cost and material availability. Type A houses use lightweight materials such as tin sheets, which offer minimal thermal resistance. Type B structures use brick masonry with concrete roofs, providing moderate stability but limited insulation. Type C units incorporate improved materials, including thicker walls and better roofing systems.

Material properties significantly affect indoor temperatures:

Material Type	Thermal Behavior	Impact on Indoor Temperature
Tin/Metal Sheets	High heat absorption	Rapid temperature rise
Brick Masonry	Moderate thermal mass	Partial temperature control
Insulated Concrete	Reduced heat transfer	Improved thermal stability

These findings highlight the importance of material selection in enhancing thermal performance, especially in hot climates.

3.3 Existing Ventilation and Thermal Conditions

Ventilation varies notably across housing types. Type A units often lack sufficient openings, resulting in poor airflow. Type B houses provide moderate ventilation through limited windows, while Type C units achieve better airflow with cross-ventilation design.

Field measurements during peak summer show clear differences:

Housing Type	Avg Indoor Temp (°C)	Relative Humidity (%)	Ventilation Quality
Type A	34.8	65	Poor
Type B	31.5	60	Moderate
Type C	28.9	58	Good

Improved ventilation correlates with lower indoor temperatures and enhanced comfort. A strong inverse relationship is observed between ventilation effectiveness and heat accumulation, emphasizing airflow as a key passive cooling strategy.

3.4 Socio-economic Profile of Residents

Residents largely belong to low-income groups with limited financial capacity to improve housing conditions or adopt mechanical cooling systems. Most are engaged in informal occupations, with modest education levels and relatively large household sizes.

Parameter	Observation
Monthly Income	Low to lower-middle range
Occupation	Informal sector (labor, services)
Education Level	Primary to secondary level
Household Size	4–7 members
Cooling Access	Mostly fans; minimal AC usage

Economic constraints significantly influence both construction quality and energy use. High occupancy density further increases indoor heat levels.

Survey results on thermal comfort indicate widespread discomfort:

Comfort Level	Percentage of Respondents
Low Comfort	42%
Moderate Comfort	38%
High Comfort	20%

These findings demonstrate that thermal comfort is shaped by both physical housing conditions and socio-economic realities. While design improvements can enhance performance, their success depends on affordability and user context, highlighting the need for integrated and practical solutions.

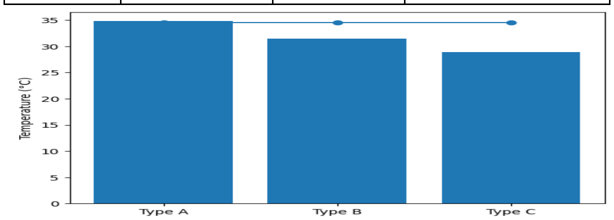
4. Results and Analysis

4.1 Thermal Performance Analysis (Engineering Aspect)

Indoor vs Outdoor Temperature

Field data reveal a clear trend of heat accumulation in poorly designed dwellings. Type A units often record indoor temperatures slightly higher than outdoor conditions due to inadequate ventilation and heat-absorbing materials. In contrast, improved designs (Type B and C) maintain lower indoor temperatures, demonstrating effective thermal buffering.

Housing Type	Avg Outdoor Temp (°C)	Avg Indoor Temp (°C)	Temperature Difference (°C)
Type A	34.5	34.8	+0.3
Type B	34.5	31.5	-3.0
Type C	34.5	28.9	-5.6

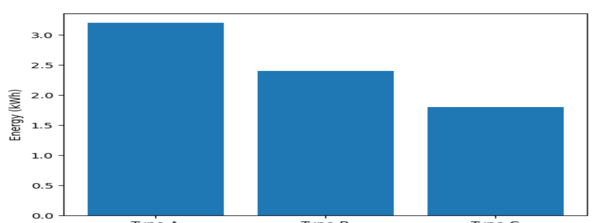


These results confirm that better design and materials significantly improve indoor thermal conditions.

Energy Consumption

Energy use is closely linked to thermal comfort. Households experiencing higher temperatures rely more on cooling devices such as fans, increasing electricity consumption.

Housing Type	Avg Daily Energy Use (kWh)	Cooling Dependency
Type A	3.2	High
Type B	2.4	Moderate
Type C	1.8	Low



Improved thermal performance reduces dependence on mechanical cooling, lowering energy demand and costs.

4.2 Mechanical System Evaluation

Ventilation Efficiency

Ventilation plays a critical role in passive cooling. The analysis shows a direct relationship between airflow and temperature reduction.

Ventilation Type	Airflow Level	Avg Temp Reduction (°C)
Poor Ventilation	Low	0–1
Single-side Openings	Moderate	1–3
Cross Ventilation	High	3–5

Cross-ventilated units achieve the greatest cooling effect, highlighting the importance of airflow in design.

Cooling Performance

In the absence of advanced HVAC systems, passive strategies and basic devices such as fans dominate. Simulation results indicate that design improvements—such as reflective roofing and better ventilation—can significantly reduce indoor temperatures.

Design Scenario	Peak Indoor Temp (°C)	Reduction (%)
Base Condition	34.2	—
Improved Design	29.8	12–14%

These findings demonstrate the effectiveness of low-cost, passive interventions in improving thermal conditions.

4.3 Social Well-being Assessment (Sociology Aspect)

Occupant Satisfaction

Thermal conditions strongly influence satisfaction levels. Residents in better-designed houses report higher comfort.

Housing Type	Satisfaction Level (%)
Type A	32
Type B	55
Type C	78

Health Impacts

Exposure to high indoor temperatures is associated with multiple health concerns.

Health Indicator	Affected Population (%)
Sleep Disturbance	41
Fatigue	38
Heat-related Stress	35

Behavioral Adaptation

Residents commonly adopt coping strategies such as increased fan use, schedule adjustments, and seeking outdoor relief. However, these are short-term solutions and do not resolve underlying structural issues.

4.4 Statistical Analysis

Correlation Analysis

Statistical results highlight strong relationships between environmental factors and occupant responses.

Variables	Correlation Coefficient (r)
Temperature vs Comfort	-0.72
Ventilation vs Comfort	+0.68
Temperature vs Health Issues	+0.61
Energy Efficiency vs Satisfaction	+0.74

Higher temperatures reduce comfort, while improved ventilation enhances it.

Regression Analysis

A regression model further evaluates the influence of key variables:

$$\text{Thermal Comfort} = \beta_0 + \beta_1(\text{Temperature}) + \beta_2(\text{Ventilation}) + \beta_3(\text{Material}) + \varepsilon$$

Variable	Coefficient (β)	p-value	Interpretation
Temperature	-0.65	<0.01	Strong negative impact
Ventilation	+0.48	<0.01	Significant positive effect
Material Type	+0.36	<0.05	Moderate positive influence

The analysis confirms that temperature is the most critical factor affecting comfort, followed by ventilation and material quality. These statistically significant findings reinforce the importance of integrated design strategies for improving both thermal performance and occupant well-being.

5. Discussion

5.1 Interpretation of Results

The study establishes a strong link between housing design, indoor thermal conditions, and occupant well-being. Poorly designed dwellings—characterized by limited ventilation and heat-absorbing materials—consistently show higher indoor temperatures, often exceeding outdoor levels. In contrast, improved structures with cross-ventilation and better materials maintain cooler and more stable indoor environments.

Statistical findings support these observations. A strong negative correlation between temperature and comfort indicates that rising heat levels directly reduce satisfaction. Conversely, ventilation shows a positive relationship with comfort, highlighting its importance in passive cooling. Regression analysis further confirms temperature as the most influential factor, followed by ventilation and material quality. While residents adopt coping strategies, these measures are insufficient, emphasizing the need for structural improvements.

5.2 Comparison with Previous Studies

The results align with earlier research that identifies poor thermal performance in low-income housing due to inadequate design and material use. Similar studies have also highlighted the importance of ventilation and material selection in improving indoor environments.

However, this study advances existing knowledge by integrating engineering and socio-behavioral perspectives. It demonstrates how physical conditions and human responses interact, particularly in resource-constrained settings.

Aspect Studied	Previous Research Insight	Present Study Finding
Indoor Temperature	High in low-income housing	Confirmed through field data
Ventilation Impact	Improves comfort	Strong positive correlation
Material Performance	Affects heat transfer	Significant in regression analysis
Social Well-being	Studied separately	Integrated with engineering analysis

This combined approach provides a more comprehensive understanding of housing performance.

5.3 Engineering vs Social Trade-offs

A key insight is the trade-off between technical solutions and socio-economic constraints. While engineering improvements—such as insulation and advanced materials—can enhance thermal performance, their cost often limits adoption in low-income communities. Similarly, mechanical cooling systems offer immediate comfort but are expensive to operate.

Intervention Type	Engineering Benefit	Social Constraint
Insulated materials	High thermal efficiency	High initial cost
Passive ventilation	Low energy requirement	Design limitations
Mechanical cooling	Immediate comfort	High operational cost
Hybrid solutions	Balanced performance	Needs awareness and support

The findings suggest that affordable, passive design strategies provide the most practical and scalable solutions.

5.4 Policy Relevance

The study highlights the need to integrate thermal comfort into housing policies. Current programs often prioritize quantity over quality, resulting in inadequate living conditions. Incorporating climate-responsive design principles—such as proper orientation, ventilation, and material selection—can significantly improve comfort without major cost increases. Key policy recommendations include promoting energy-efficient building guidelines, encouraging the use of locally suitable materials, integrating passive strategies into housing schemes, and increasing community awareness. Such measures can enhance both energy performance and social well-being, supporting more inclusive and sustainable urban development.

6. Recommendations

The study highlights that improving thermal comfort and well-being in low-income housing requires a balanced approach integrating design, passive strategies, policy support, and community participation. The following recommendations emphasize affordability, practicality, and scalability.

6.1 Design Improvements for Low-Cost Housing

Thermal performance can be significantly enhanced through simple design modifications rather than costly technologies. Key improvements include better building orientation, increased wall thickness, and the use of reflective or insulated roofing materials. Enhancing window placement for cross-ventilation and incorporating shading elements can further reduce indoor heat.

Design Element	Recommended Improvement	Expected Impact
Roof Design	Reflective coating / insulation	Reduced heat absorption
Wall Construction	Thicker or cavity walls	Improved thermal resistance
Openings	Cross-ventilation design	Enhanced airflow
Orientation	Minimize direct solar exposure	Lower indoor temperature
Shading Devices	Overhangs, vegetation	Reduced solar heat gain

These interventions are cost-effective and feasible using local materials.

6.2 Passive Cooling and Heating Strategies

Passive strategies are essential for reducing energy dependence while maintaining comfort. Techniques such as natural ventilation, shading, and thermal mass can effectively lower indoor temperatures and stabilize variations.

Strategy Type	Function	Temperature Impact
Natural Ventilation	Air circulation and cooling	Moderate reduction
Shading	Blocks solar radiation	Significant reduction
Thermal Mass	Stores and releases heat	Stabilizes temperature
Reflective Surfaces	Reduces heat absorption	Moderate reduction

Combining these strategies yields better results than isolated applications, supporting an integrated design approach.

6.3 Policy Suggestions

Policy interventions are crucial to ensure long-term improvements in housing quality. Current housing programs should move beyond quantity and incorporate thermal performance as a core criterion. Governments can promote energy-efficient practices through regulations, incentives, and awareness programs.

Policy Measure	Short-Term Benefit	Long-Term Outcome

Policy Measure	Short-Term Benefit	Long-Term Outcome
Subsidized materials	Lower construction cost	Improved housing quality
Design guidelines	Standardized practices	Better thermal performance
Awareness programs	Increased knowledge	Behavioral change
Skill development	Improved construction	Sustainable practices

Such measures can make energy-efficient housing accessible to low-income populations.

6.4 Community-Level Interventions

Community involvement plays a vital role in implementing sustainable solutions. Residents often rely on adaptive behaviors, indicating their willingness to engage with practical improvements. Awareness campaigns and training programs can help communities adopt low-cost techniques for better ventilation and heat reduction.

Key initiatives include promoting energy awareness, training in basic construction improvements, and encouraging shared solutions such as tree planting and shaded community spaces. Collective efforts can enhance local microclimates and improve living conditions.

Overall, integrating technical solutions with policy support and community engagement offers a sustainable pathway to improving thermal comfort and quality of life in low-income housing.

7. Conclusion

7.1 Summary of Key Findings

This study explored the relationship between energy-efficient housing design, indoor thermal conditions, and social well-being in low-income communities. The findings confirm that design parameters—such as material selection, ventilation, and layout—directly influence indoor thermal performance. Poorly designed houses, particularly those with inadequate airflow and heat-absorbing materials, tend to experience higher indoor temperatures, often exceeding outdoor levels.

In contrast, improved housing designs incorporating cross-ventilation, appropriate orientation, and thermally efficient materials maintain lower and more stable indoor temperatures. These improvements significantly enhance occupant comfort, reduce health risks, and increase satisfaction. Statistical analysis further highlights strong relationships between environmental and social factors, with temperature emerging as the most critical variable, followed by ventilation and material quality.

7.2 Interdisciplinary Contributions

The study contributes to multiple disciplines by integrating technical and social perspectives.

Field	Key Contribution
Civil Engineering	Demonstrates impact of design and materials on thermal performance
Mechanical Engineering	Highlights effectiveness of passive and low-energy systems
Sociology	Connects thermal conditions with health, behavior, and well-being

This integrated approach provides a comprehensive framework that combines engineering efficiency with human-centered insights.

7.3 Practical Implications

The research offers actionable insights for improving low-income housing. It shows that simple and affordable interventions—such as better ventilation, reflective roofing, and optimized orientation—can significantly improve indoor conditions without increasing energy demand.

Stakeholder	Key Implication
Policymakers	Integrate thermal comfort into housing policies
Engineers/Designers	Adopt cost-effective, passive design strategies
Communities	Promote awareness and skill development

These measures can enhance living conditions while maintaining affordability, making them suitable for large-scale implementation.

7.4 Scope for Future Research

While the study provides valuable insights, further research is needed to broaden its applicability. Future studies can examine different climatic regions to enable comparative analysis and assess seasonal variations in thermal performance. Advanced tools such as real-time monitoring and simulation models can improve accuracy and depth of analysis.

There is also potential to explore renewable energy integration, such as solar-assisted ventilation systems, within low-income housing. From a social perspective, future work can focus on behavioral interventions, community participation, and policy effectiveness at the ground level. Such efforts will support the development of scalable, sustainable, and inclusive housing solutions.

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