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Thermal dispersion study of roof and wall materials with chemical pretreatments for energy reduction

The corrections made in this section will be reviewed by journal production editor.

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Abstract

This study focuses on reducing heat losses in residential buildings, specifically in the climatic conditions of Ranchi, India. The analysis emphasizes the use of Expanded Polystyrene as an insulating material to address challenges associated with high thermal distribution rates in building envelopes. High thermal distribution in building envelopes and inefficient thermal systems are the primary drivers of increased energy consumption. Thermal distribution of the building envelope contributes to high energy consumption which shield the internal environment from exterior factors such as heating, cooling, humidity, rain, wind, snow, light, noise and air pollution depending on the location. In the month of June, average thermal flows reached $4.9\,W/m^2$ for walls and $18.6\,W/m^2$ for roofs due to higher ambient temperatures and solar irradiance. During winter, heat dispersion was reduced to $2.5\,W/m^2$ for walls and $1.7\,W/m^2$ for roofs, demonstrating the insulating efficiency of Expanded Polystyrene compared to conventional materials. This study demonstrates that Expanded Polystyrene significantly reduces heat losses by 90% in roofs and 47% in walls compared to conventional structures without insulation, showcasing its efficiency as an insulating material. Its application in real-world residential buildings can lead to substantial energy savings and improved thermal comfort, making it a practical solution for energy-efficient construction.

Keywords COMSOL multiphysics; thermal energy; building heat transfer; energy efficiency; expanded polystyrene

Funding Information

Funding Source :	Deanship of Scientific Research at King Khalid University (KKU) through the Research Group Program
Funder DOI :	
Award Number :	R.G.P.2/552/45

1 Introduction

In recent years, efforts have been made to decrease the pollutants emission by reducing the human activities impact on the environment. Studies have been carried out for optimising the conversion rate and the economic feasibility of the alternative fuels [1]–[5]. In buildings, research and industries are identifying the effects of outer walls to reduce the thermal expenditure. External walls allow the users to conduct the activities in safe conditions. The building should ensure structural safety and protection from climatic variations to the individuals. The building envelope should avoid all the sources of noise and allows to visualize association with the environment, which would lead to optimal use of light from the external environment [6]–[11]. In fact, a well-designed building envelope cannot give all kinds of comfort and visual conditions to the users [12], [13]. Additional systems like air-conditioning and lighting systems can be able to meet the necessary comfort requirements. Mostafaeipour et al. (2019) studied the overuse of the additional installations leads to detrimental environmental and economic impact because of the poor building envelope design which, cannot be ignored [14]. The imperfect designing of the building envelope leads to higher energy consumption and lower building energy efficiency. Increasing the building energy efficiency and minimizing energy consumption of the building can be achieved by installing good thermal insulation and minimizing the size of the air-conditioning system of the building [15], [16] Espindola et al. (2021) examines the relationship between energy use, possible energy savings, and the impact of energy assessments in various industries [17]. Two measures are used to determine the correlation: (1) energy intensity utilisation (EIU) and (2) specific energy consumption (SEC). This study uses the Standard Industrial Classification (SIC) code to classify the assessments for 67 sectors from 2015 to 2019. The findings reveal that energy conservation and consumption are linearly connected. In addition, the energy evaluation increases energy performance in smaller businesses more significantly than in larger sectors. Qandil et al. (2021) studied the energy assessments and analyses of 11 wastewater treatment plants [18]. Plants can save up to 44,158 MWh of energy consumption, or 47 percent of overall electricity consumption, with a 17 percent reduction in total utility bills and a cost savings of around 2.5 million dollars after examining the present assisted energy system, according to the inquiry. Most energy-saving recommendations have a five-year payback period. With a total range reduction of 13–35 million kg of CO_2 based on the speed decrease percentage, a large amount of greenhouse gas emissions can be reduced. Melikov et al. (2016) studied for optimizing the energy and management cost of the air-conditioning system in the building, a proper envelope design is necessary [19]. Rather than changing the building envelope, it is much easier to improve the efficiency of the plant. The building envelope consists of two different categories: transparent and opaque. Vakiloroaya et al. (2014) examines the elements that minimize heat transmission between the environment and building are termed as opaque and provide sufficient natural light to the building are transparent elements [20]. Lower thermal insulation in the building comes under the category of transparent elements if compared with opaque elements. Bellia et al. (2006) examined that the recommended transparent value should be between 10 and 15% of the envelope surface of the building by providing sufficient visual interaction [21]. To the vertical wall structure of the building, an external covering is applied, exposed to the atmosphere. The external wall covering provides mechanical stress resistance, protects from chemical agents, and give an aesthetic finish to the building wall. Vickers et al. (2017) studied the ceramic as an external layer to the building wall has a high melting point, high insulating properties, low thermal conductivity, and resistance to heat transmission [22]. It is used as thermal insulation in many countries by installing it on the outer walls of the building as shown in Table 1 [12].

Table 1:

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Review of thermal dispersion.

Authors	Findings
Mostafaeipour	Overuse of the additional installations leads to environmental and economic impact because of the poor building envelope design
C. Liang et al.	Poor design of the building envelope leads to higher energy consumption and lower building energy efficiency
A.K. Melikov	The building envelope consists of two different categories: Opaque and transparent
V. Vakiloroaya et al.	Lower thermal insulation in the building comes under the category of transparent elements if compared with opaque elements
L. Aditya et al.	The ceramic as an external layer to the building wall has a high melting point, high insulating properties, low thermal conductivity, and resistance to heat transmission. It is used as thermal insulation in many countries by installing it on the outer walls of the building
T. Bergman et al.	COMSOL multiphysics finite elements simulation software, which helps to solve the user complex analysis

Expanded Polystyrene (EPS), a white foam plastic material generated from polystyrene solid beads, is widely used as an insulating material. In this study, EPS blocks manufactured by Supreme Petrochem Ltd., India were proposed for thermal insulation. EPS enhances the building's structural and design ability due to its lightweight, moldability, and strength. Recognized as a conventional insulating material since the 1950s, EPS has seen rapid advancements in its applications. It is currently utilized in buildings for providing sustainable indoor environmental quality, energy efficiency, and durability. EPS's durability lies in its resistance to moisture absorption, UV radiation, and physical degradation, which ensures its thermal performance remains consistent over time. Furthermore, EPS materials are less prone to wear and tear, reducing maintenance requirements and replacement frequency. This long-lasting nature makes it a cost-effective and sustainable choice for energy-efficient construction. The main objective of this paper is to analyse the thermal insulation characteristic of EPS, numerically simulating through the Finite Element Method (FEM) approach. The climatic conditions of Ranchi are considered and analysed by identifying the heat flux of the materials used in this paper. The materials include roof and wall building materials provided by the Energy Conservation Building Code (ECBC) [23].

The results generated in this analysis should be able to decrease energy consumption. In addition to the thermal analysis of the energy consumption analysis is also performed to calculate the energy-saving potential of the building based on two different roofs and wall materials. In 2007, for setting the standards in maintaining minimum energy consumption for commercial buildings, Government of India launches the Energy Conservation Building Code (ECBC). As part of the National Action Plan for Climate Change, a mission has been enacted called National Mission for Enhanced

Energy Efficiency by the Indian government in 2009. ECBC is a model code at the national level, but it becomes mandatory for adopting and implementing it in the state or local administration jurisdiction. The mission launched various programs to suggest measures and improve energy efficiency in different. The practical implementation of ECBC achieves intended energy savings. ECBC benefits will significantly help the states in avoiding carbon-intensive projects in India.

The researches have been carried out for the effects of outer wall to reduce thermal expenditure and overuse of AC and lightening leads to detrimental environment. However, on residential buildings using Expanded Polystyrene as an insulating material for both the roof and walls of a buildings is a new concept. Residential buildings account for a heat loss of 90% in roofs and 47% in walls than the wall's structure having no thermal insulator. Hence, it is important to find out the energy savings strategy in the buildings.

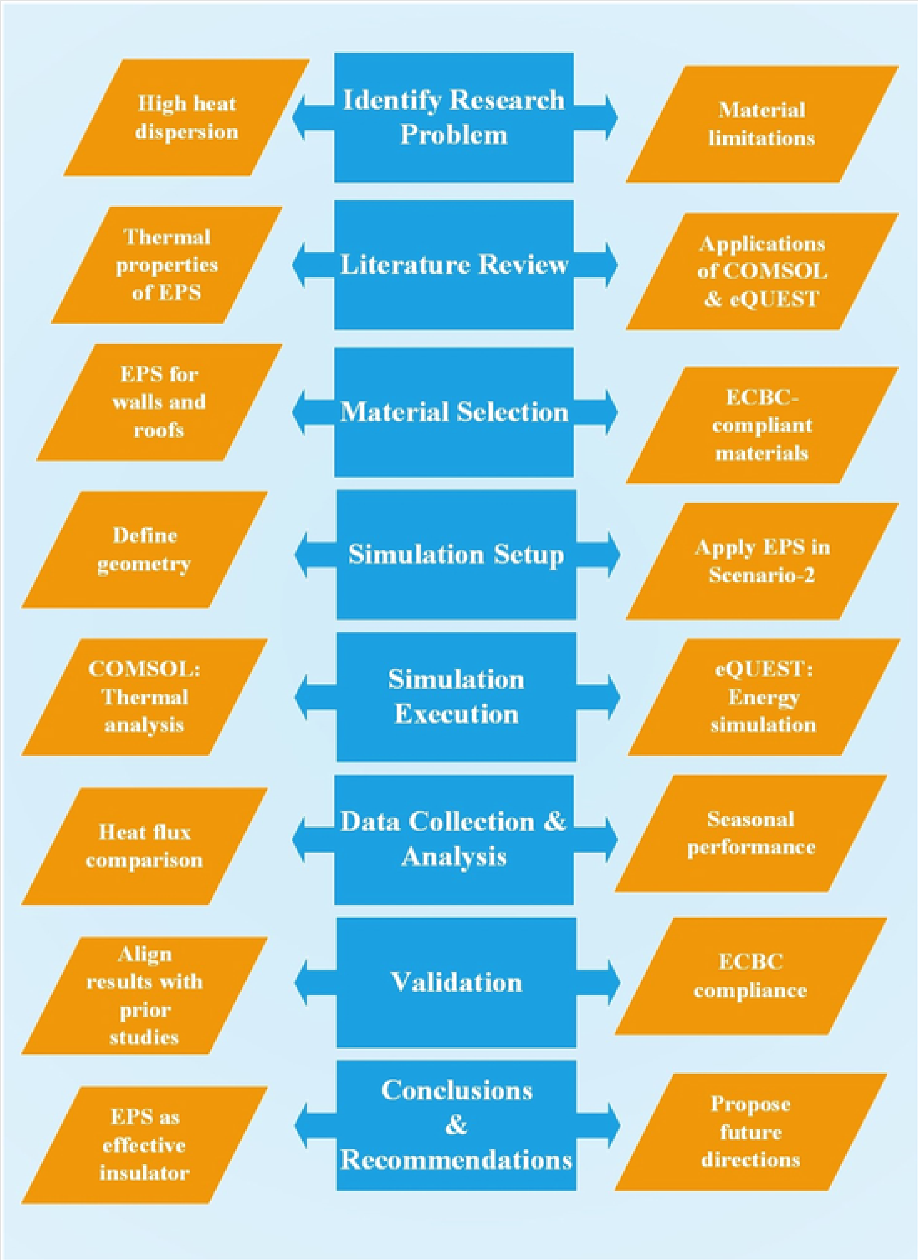
The motivation of the study is to reduce thermal insulator and energy consumption in the residential building. The objective of this study is to perform energy conservation analysis of residential buildings based on the Indian climatic conditions. The building parameters (wall-roof materials and window materials) are based on the report of Energy Conservation and Building Code (ECBC) which was approved by the Government of India.

This study focuses on the investigation of Expanded Polystyrene (EPS) as an effective thermal insulation material for building envelopes, specifically under Indian climatic conditions. Previous research has explored various conventional and natural insulating materials, including sugarcane bagasse, oil palm fibers, and bio-composites, to improve the thermal performance of buildings. While these materials have shown potential for reducing heat flux, they often face limitations in durability, scalability, and consistent thermal performance under varying environmental conditions. Unlike prior studies, this research uniquely emphasizes the application of EPS, a lightweight, durable, and cost-effective material with a low thermal conductivity of 0.035 W/mK, as a solution to mitigate thermal dispersion in building envelopes. The novelty of this study lies in its approach to quantifying the energy efficiency and heat flux reduction achieved by integrating EPS into walls and roofs. Through numerical simulations conducted using COMSOL Multiphysics and eQUEST, the thermal performance of EPS was validated under realistic scenarios. The results demonstrated a significant reduction in heat loss, with up to 90% in roofs and 47% in walls compared to non-insulated configurations. These findings highlight the scalability and practicality of EPS for addressing energy consumption challenges in residential buildings. Moreover, this study bridges the gap in existing literature by addressing the long-term performance of EPS, including its resistance to environmental degradation, cost-effectiveness, and ease of availability in local markets. Unlike materials studied in previous works, which often require specific processing or exhibit limitations in extreme climatic zones, EPS offers consistent performance across diverse conditions. By demonstrating its potential for widespread adoption, this work contributes to advancing sustainable building practices and energy conservation strategies, particularly in developing regions with high energy demands. These findings underscore the critical role of EPS in reducing greenhouse gas emissions and achieving energy-efficient construction practices.

2 Methodology and materials

Simulation software such as COMSOL Multiphysics (version 5.5, COMSOL Inc., Sweden) was employed to perform the numerical analysis, enabling detailed modeling of heat transfer phenomena [24]. Additionally, energy simulations were conducted using eQUEST, a DOE-2-based software developed by the U.S. Department of Energy, USA, to evaluate the building's energy performance under various scenarios. Materials proposed in this study included EPS blocks with a density of 24 kg/m^3, procured from Supreme Petrochem Ltd., India, which served as insulating material for walls and roofs. Furthermore, cement plaster and bricks were proposed from Everest Industries Ltd., India, adhering to ECBC guidelines to ensure material quality and compliance. Figure 1 has exhibited the methodology of current study.

Figure 1:



Research methodology of the current work.

2.1 Simulation software

COMSOL Multiphysics finite elements simulation software, which helps to solve the users all the complex analysis present in the problem [25]. COMSOL Multiphysics 5.5 has been used for the simulation. This software makes it possible to study and modify the heat transfer phenomena (conduction, convection, and radiation) in solids. The simulation in COMSOL starts with defining the geometry, selecting materials, assigning the materials, selecting the required physics and study, providing the inputs for simulation, and selecting the interface for solving the physical problems. The users have to set a boundary condition in the case of any time dependent scenarios. Study of stationary subjects are also allowed in this software. The spatial domain should be defined by turning the mesh node. Depending on the available computational resources, processing starts [26]. The eQUEST software allows the user to develop the 3-dimensional model of the building based on the requirement. The climatic conditions of the building are also considered in this software which directly impacts the energy consumption of the building. Building energy simulation, includes building location, wall-roof material properties, window glazing properties, daylight control system, solar heating, ventilation, and air conditioning (HVAC) system, and calculating the energy conservation potential of a building [27]–[29].

2.2 Wall – roof materials and its properties

Energy-efficient building can be achieved by constructing the walls and roof with low thermal conductivity and better insulation for existing and new buildings. The study aims to determine the energy savings potential of the low thermal conductivity and insulating materials. In fact, the ECBC has suggested the buildings' materials for the buildings based on the U-value (overall heat coefficient) and R-value (overall thermal resistance) for energy efficiency in buildings but left to the designer to choose the materials available in the market. To achieve the energy efficient building objective, thermal analysis of wall and roof materials have been carried out in this paper based on the materials provided by the ECBC. Two materials from the wall and roof with lower thermal conductivity and better insulating materials having different thicknesses are taken from the ECBC report and analysed. Table 2 lists wall materials based on their U-values as specified in the ECBC guidelines. The materials with lower U-values, such as AAC blocks (0.55 $W/m^2 K$), provide better thermal resistance. Materials with higher U-values, such as dense concrete hollow blocks (3.01 $W/m^2 K$), are less effective in reducing heat transfer, demonstrating the importance of material selection for energy-efficient construction.

Table 2:

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Wall materials provided by the ECBC in its report based on U-value.

S. No.	Wall specification	U value ($W/m^2 K$)
1	20.00 cm brick + 1.25 cm cement plaster + 1.25 cm cement plaster	2.28
2	22.5 cm brick + 1.25 cm cement plaster + 1.25 cm cement plaster	2.13
3	7.5 cm brick + 1.25 cm cement plaster + 7.5 cm brick + 5.0 cm air gap + 1.25 cm cement plaster	1.80
4	5.0 cm air gap + 11.25 cm brick + 1.25 cm cement plaster + 1.25 cm cement plaster + 11.25 cm brick	1.55
5	22.5 cm brick + 1.25 cm cement plaster + 1.25 cm cement plaster + 2.5 cm expanded polystyrene	0.85
6	1.25 cm cement plaster + 2.5 cm expanded polystyrene plaster + 22.5 cm brick + 1.25 cm cement	0.85
7	20 cm dense concrete-hollow block (2 holes)	3.01
8	20 cm dense concrete-hollow block (3 holes)	2.79
9	5 cm foam concrete + 1.25 cm cement plaster + 1.25 cm cement plaster + 11.25 cm concrete	0.99
10	20 cm AAC block + 1.25 cm cement plaster + 1.25 cm cement plaster	0.78
11	30 cm AAC block + 1.25 cm cement plaster + 1.25 cm cement plaster	0.55

Table 3 outlines the thermal properties of roof materials. The inclusion of EPS in materials like extruded polystyrene with RCC (U-value = 0.52 $W/m^2 K$) significantly improves thermal insulation compared to plain RCC (U-value = 3.59 $W/m^2 K$). This underscores EPS's potential in reducing heat gain through roofs in hot climates.

Table 3:

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Roof materials provided by the ECBC in its report based on U-value.

S. No.	Specification of roof	U value (W/m^2 K)
1	100 mm RCC	3.59
2	100 mm lime concrete + 100 mm RCC	2.78
3	50 mm foam concrete + 100 mm RCC + waterproofing	1.08
5	50 mm cinder concrete + 100 mm RCC + 50 mm brick tile	2.07
6	75 mm cinder concrete + 100 mm RCC + 50 mm brick tile	1.76
7	50 mm mud phuska + 115 mm RCC + 50 mm brick tile	2.31
8	Inverted clay pots with mud phuska + 100 mm RCC	2.34
9	Extruded polystyrene 25 mm – 36 kg/m^3 + 100 mm RCC	0.74
10	Extruded polystyrene 30 mm – 36 kg/m^3 + 100 mm RCC	0.65
11	Extruded polystyrene 40 mm – 36 kg/m^3 + 100 mm RCC	0.52

2.3 Building description

A ten-story multifamily (mid-rise) building over an underground parking facility based on the climatic location of Smart City (Ranchi), Jharkhand, India, is selected as a model building for this study. Table 4 presents the wall-roof dimensions and properties for baseline (type-1) and proposed (type-2) building models. The building floor area for both baseline and proposed models are considered to be 1,858 m^2, each floor area is 186 m^2, and floor to floor height is 3 m, as shown in Table 5. The window to wall ratio is maintained at 22 %; building orientation is kept at East based on the location of the building model. Table 5 details the building's design parameters, including the floor area, zoning pattern, and window-to-wall ratio. The consistent dimensions and zoning ensure accurate simulation results, while the east orientation reflects typical residential building configurations in Ranchi. Figure 2 represents the H-shaped building model selected for energy consumption analysis, designed based on the climatic conditions of Ranchi, India. The model reflects a typical residential structure with a 22 % window-to-wall ratio, which optimizes natural daylight while limiting solar heat gain. This configuration allows for a realistic simulation of thermal and energy performance.

Table 4:

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Building material properties.

Material	Type-1	Type-2	Properties
Wall	1.25 cm cement plaster + 22.5 cm brick + 1.25 cm cement plaster (U-value = 2.13 W/(m^2 K))	1.25 cm cement plaster + 22.5 cm brick + 2.5 cm expanded polystyrene + 1.25 cm cement plaster (U-value = 0.85 W/(m^2 K))	**Cement plaster:** density (ρ) = 1,762 kg/m^3 thermal conductivity (k) = 0.721 W/(m K) specific heat capacity (Cp) = 840 J/(kg K)

			Brick: density (ρ) = 2,000 kg/m^3 thermal conductivity (k) = 0.5 W/(m K) specific heat capacity (Cp) = 900 J/(kg K) **Expanded** **polystyrene:** density (ρ) = 11.5 kg/m^3 thermal conductivity (k) = 0.05 W/(m K) Specific heat capacity (Cp) = 1450 J/(kg K)
Roof	100 mm reinforced cement concrete (RCC) (U-value = 3.59 W/(m^2 K))	100 mm RCC + 60 mm expanded polystyrene (U-value = 0.482 W/(m^2 K))	**Reinforced cement** **concrete (RCC):** density (ρ) = 2,288 kg/m^3 thermal conductivity (k) = 1.58 W/(m K) specific heat capacity (Cp) = 880 J/(kg K) **Expanded** **polystyrene:** density (ρ) = 24 kg/m^3 thermal conductivity (k) = 0.035 W/(m K) specific heat capacity (Cp) = 1340 J/(kg K)
Window glass	Type	Dimensions	Properties
	Double low-E (clear)	Length = 305 cm height = 183 cm thickness = 38 mm	Emissivity, ε = 0.2, SHGC = 0.67, VT = 0.78

Table 5:

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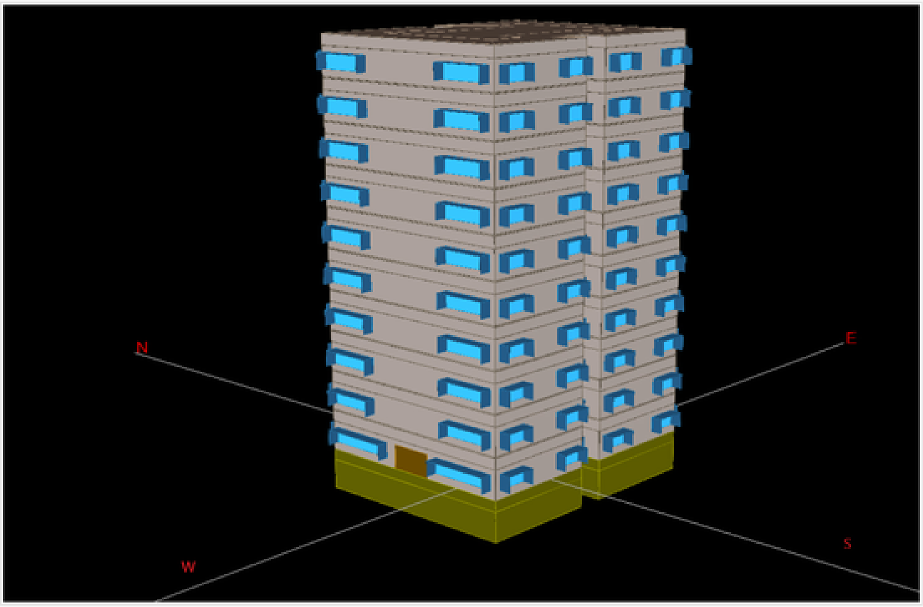
Building parameters.

Parameters	Values
Zoning pattern	Perimeter/core
Aspect ratio	1
Floor to floor height	4.5 m

Floor to ceiling height	4 m
Building area	1,858 m^2
Building shape	'H'-shaped
Perimeter zone depth	7.6 m
Building orientation	East
Window-to-wall ratio	22 %

Figure 2:



Building model for energy consumption analysis.

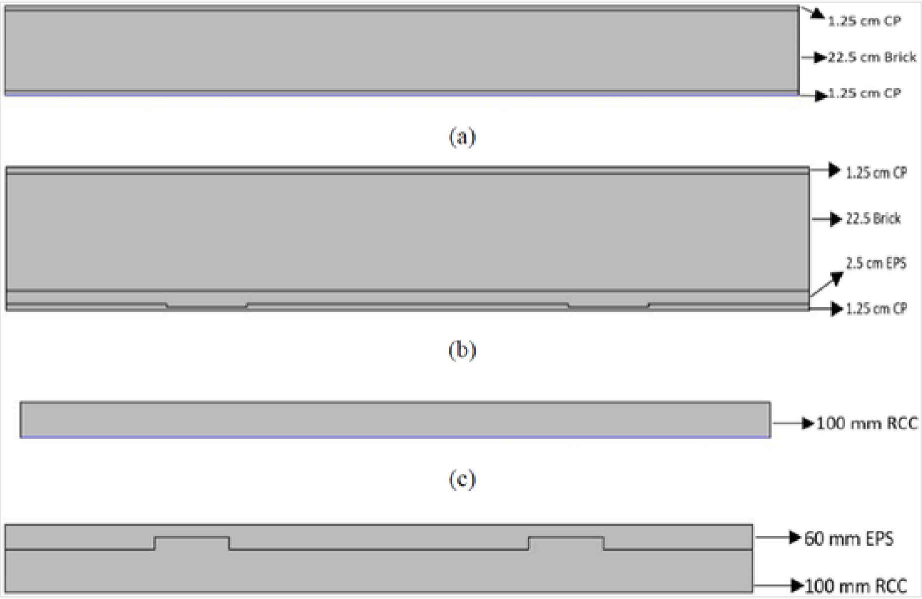
2.4 Geometry and simulation scenarios

The geometry for both wall and roof materials for the building model is shown in Figure 3(a–d). In this study, the EPS is used as insulating materials by fixing on specific support in both wall and roof of the building. The main objective is the determination of heat transmission through the materials. The dimensions of the slab considered for the analysis are 2 m × 2 m with a thickness varying between 60 mm and 225 mm for both materials. The placing of the material is on the façade of the building which is exposed to external convective conditions resulting in transmission of heat. The following phenomena are considered in this study:

- External convective heat transfer between the environment and the external wall.
- Internal convective heat transfer between the indoor environment and the internal walls.
- Conduction between the internal wall components.
- Convective heat transfer between the external environment and external components of the building.
- Conduction heat transfer between the roof components.

Figure alignment: The figure layout displayed in this section is not how it will appear in the final version. As per journal style, figures will only be left aligned. The presentation below is for the sole purpose of providing corrections to the figures. To view the actual presentation of the figures, please click on the PDF located at the top of the page.

Figure 3:



Q8 Geometry for Wall and Roof Materials, (a) Wall geometry for scenario-1, (b) wall geometry for scenario-2, (c) roof geometry for scenario-1, (d) roof geometry for scenario-2.

In this study, thermal analysis is performed in two scenarios which is discussed in this section. The geometry of the wall and roof components is shown in Figure 3(a–d).

Two scenarios are considered for the thermal analysis of both the wall and roof materials. Scenario-1 and Scenario-2 are the simulation that are computed to analyse the heat transfer of different components. In the first scenario, wall and roof materials with high U-values are considered as shown in the Table 4 and observed the heat transfer phenomena. The geometry of the wall and roof materials in Scenario-1 is shown in Figure 3(a) and (b), respectively. The wall comprises of Cement Plaster (CP), and the brick, and roof are composed of Reinforced Cement Concrete (RCC). There is no insulating material used in this scenario. From Table 3, the type-1 materials considered for the analysis have a high U-value compared to type-2 materials. In the second scenario, wall and roof materials with low U-value are considered in Table 4. The geometry of the wall and roof materials are shown in Figure 3(c) and (d), respectively. In this scenario, the insulating material is added to both wall and roof to observe the heat transfer phenomena. The wall is composed of CP, Brick and EPS materials and roof is composed of RCC and EPS materials as shown in the Table 4 (Type-2).

The windows in the model building are double low-E material, the most used material in residential buildings. The typical thickness of the CP is 12.5 mm, but the thickness can be increased in certain circumstances. The plastering to the walls of the building is used mainly for a smooth finish, wall protection to absorb the moisture from the walls and avoid dripping and condensation. The materials in Scenario-1 and 2 are based on the ECBC report and these are the easily available materials in the market as shown in Tables 2 and 3. Thermal analysis is performed for both the scenarios, and the results of the simulation are compared. Scenario-1 is taken as the reference to compare the simulation results as the first scenario has the most basic wall and roof materials. The simulations' thermal dispersion values are intended as the average heat flux passing the wall's surface through the internal and external environment along the 12 months of the reference year and location.

2.5 Convective heat transfer coefficient data based on the ambient conditions

The simulation of the different scenarios in this study has taken the external environmental convection conditions. The convection phenomena are calculated using the dimensionless numbers Re and Pr for external convection and for internal convection is Gr and Pr. In this study, the internal and external convection is calculated by using the formula [30].

$$h_{cw} = 12.12 - 1.16u + 11.6u^{1/2} \tag{1}$$

Where,

h_{cw} = Convective heat transfer coefficient

u = wind speed

The monthly temperatures and the wind speed values referred to the year 2019 are obtained for Ranchi as a reference location. The values of ambient temperature, surface pressure, relative humidity, external wind speed and precipitation rate is taken from the NASA Power Data Access Viewer are shown in Table 6 [31]. The internal wind speed is taken roughly based on the seasonal variations ranging from 0.15 m/s to 0.4 m/s. The values from Table 5 are monthly ambient data of Ranchi city, India. The Solar Irradiance value is increasing from 1,045 W/m^2 to 1,121 W/m^2 in April to June due to the summer and decreases from 1,099 W/m^2 to 659 W/m^2 in July to December due to the winter.

Table 6:

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Monthly data for 2019 (reference year) and region Ranchi, India.

Month	Ambient temperature (T_{amb} °C)	Surface pressure (P_{amb} kPa)	Relative humidity (ϕ_{amb} %)	Precipitation rate ($P_{o,amb}$ m/s)	Solar irradiance (W/m^2)
January	24.21	95.83	47.95	0.1	695
February	19.83	95.64	44.84	1.3	808
March	24.17	95.4	38.77	1.1	944
April	30.3	95.02	31.09	1.1	1,045
May	32.63	94.73	31.43	1.7	1,095
June	31.93	94.42	52.33	3.3	1,121
July	27.31	94.32	81.33	8.9	1,099
August	26.2	94.38	87.83	11.6	1,055
September	25.28	94.89	89.55	10.4	974
October	22.5	95.43	86.48	5.54	849
November	18.19	95.61	81.71	0.03	721
December	14.43	95.85	80.02	0.68	659

Although heat loss and gain can occur at any point along the building's envelope. Heat gain, often known as solar gain, is the opposite of heat loss. Heat gain happens when radiant heat from the sun shines through the window and warms the area. It is also an indicator of a low U value.

The main objective of this study is to enhance the building performance by using efficient building materials. This study helps the designer to construct a proper energy management framework in the building. Cooling and heating loads are also the major energy consumption apart from lighting in the building and explained as follows

- Cooling load [KWh]: To maintain thermal comfort and decrease cooling load during humid summertime, as the proportion of heat must be expelled from a house.

- Heating load [KWh]: To minimise the heating load during wintertime operating temperature of the building must be increased through ventilation and building envelope.

Solar lamps and electricity from solar panel does not require power from the grid for running building. The vertical landscaping reduces the heat island effect by mounting solar integration on the building. It acts as insulation and reduces the heat that goes into the building. The construction allows daylight and natural ventilation in all spaces. Adjustable automatic windows to cut off supply from the grid during summers. In winter inventor provide lighting and heat.

3 Results and discussions

This study performs a thermal analysis of roof and wall materials in COMSOL Multiphysics to evaluate average thermal heat flow under two scenarios. The results demonstrate significant differences in thermal performance between the scenarios due to the use of Expanded Polystyrene (EPS) as an insulating material. The reduction in conductive heat transfer is primarily attributed to EPS's low thermal conductivity, which significantly increases the thermal resistance ($R = d/k$). Additionally, the reduced convective exchange across the insulated building envelope contributes to maintaining stable indoor temperatures. The energy simulation of a residential building using the same wall and roof materials is performed in eQUEST Simulation software to determine the energy efficiency of the building. The average surface heat flux values of scenario-1 are considered as the reference value. The following subsections discuss two simulation scenarios.

3.1 COMSOL simulation results

The thermal simulation results reveal that heat dispersion and thermal flux are significantly reduced when EPS is incorporated. The physics behind this mechanism can be attributed to:

- **Conduction:** EPS's low thermal conductivity minimizes heat transfer through the building envelope. According to Fourier's law of heat conduction, the inclusion of EPS reduces the heat flux by increasing the material's thermal resistance.

- **Convection:** External convective heat transfer between the building envelope and the environment is influenced by ambient wind speeds. The study calculates convective heat transfer coefficients using dimensionless numbers such as Reynolds and Prandtl numbers, leading to improved heat insulation in the presence of EPS.

- **Radiation:** The solar irradiance values observed during summer months are mitigated by the insulating properties of EPS, which reduce heat gain by limiting thermal radiation penetration.

EPS is widely recognized for its superior insulating properties due to its unique structure of air-filled cells. Its low thermal conductivity, coupled with resistance to moisture absorption and UV radiation, ensures long-term performance. Tables 7 and 8 compare the average thermal flow for Scenario-1 (without insulation) and Scenario-2 (with EPS insulation). The negative values indicate an average thermal flow from higher temperature component to lower temperature component. Higher thermal flow means low thermal insulating efficiency.

Table 7:

The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To view the actual presentation of the table, please click on the PDF located at the top of the page.

Average thermal flow of wall and roof materials of first scenario.

Month	Wall scenario-1	Roof scenario-1

	average thermal heat flow (W/m^2)	average thermal heat flow (W/m^2)
January	−4.648	−16.771
February	−4.267	−15.524
March	−2.443	−8.883
April	−3.117	−11.538
May	−4.194	−15.906
June	−4.908	−18.584
July	−3.684	−13.942
August	−2.973	−11.309
September	−3.814	−14.514
October	−3.820	−14.238
November	−2.385	−8.537
December	−3.991	−14.352

Table 8:

The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To view the actual presentation of the table, please click on the PDF located at the top of the page.

Average thermal flow of wall and roof materials of second scenario.

Month	Wall scenario-2 average thermal heat flow (W/m^2)	Roof scenario-2 average thermal heat flow (W/m^2)
January	−2.457	−1.734
February	−2.252	−1.594
March	−1.290	−0.913
April	−1.641	−0.986
May	−2.198	−1.552
June	−2.573	−1.817
July	−1.931	−1.364
August	−1.558	−1.100
September	−1.998	−1.411
October	−2.008	−1.420
November	−1.262	−0.891
December	−2.111	−1.495

The results, as shown in Tables 7 and 8, indicate that the average thermal flow is highest in Scenario-1 during June due to increased ambient temperatures and solar irradiance. By contrast, Scenario-2 demonstrates up to a 40% improvement in thermal insulation performance annually, as evidenced by reduced average heat flux values. The reduced thermal flow during summer and winter months demonstrates EPS's effectiveness in minimizing heat transfer, reducing cooling and heating loads.

3.1.1 Scenario-1

The average thermal flow is significantly higher in the first scenario due to the absence of insulating materials in the wall and roof structures. The highest average thermal flow is recorded in June for both wall and roof materials, attributed to elevated ambient temperatures and increased solar irradiance, as presented in Table 5. Conversely, during the winter season (November to February), thermal flow from the wall and roof materials is notably lower, resulting in reduced heat dispersion compared to other seasons.

Tables 7 and 8 present the heat flow tendencies across the internal surfaces for the seven materials investigated. Negative values indicate heat flow exiting the internal environment, highlighting internal thermal losses and reduced insulating efficiency. Among the materials, Expanded Polystyrene (EPS) demonstrates superior performance by providing effective thermal resistance. During winter, EPS significantly reduces heat dispersion and outgoing thermal flow from the building, while in summer, it substantially minimizes incoming heat flow. This reduction in heat transfer ensures a stable indoor temperature, lowering the demand for air conditioning. As a result, EPS not only decreases energy costs but also contributes to reduced pollutant emissions, making it a highly effective and sustainable choice for thermal insulation.

3.1.2 Scenario-2

In the first scenario, where no insulating material is applied to the wall and roof structures, the average heat flow is significantly high. This is particularly evident in June, where elevated ambient temperatures and increased solar irradiation result in higher thermal flow through both wall and roof materials. Conversely, during the winter months (November to February), the thermal flow from these materials is noticeably lower, leading to reduced heat dispersion compared to other seasons.

Among the materials investigated, Expanded Polystyrene (EPS) stands out as the most effective thermal insulator. The thermal flow acting on the internal surface where the building wall connects with the ready-to-use insulator is detailed in the final column of Table 7. The inclusion of EPS reduces heat loss significantly compared to the non-insulated scenario, achieving an average annual improvement in thermal insulation performance of approximately 40%. This highlights EPS's efficiency in mitigating heat transfer and enhancing energy conservation.

During daylight hours, EPS remains active and consistently provides its insulating benefits by reducing heat flow, contributing to stable indoor temperatures. However, at night, when solar irradiation is absent, EPS's active role diminishes, leading to minimal or no additional insulating impact on the building. Despite this limitation, EPS's overall performance in reducing heat transfer during peak thermal load periods makes it a highly effective and sustainable solution for energy-efficient building design.

3.1.3 Validation

The monthly heat flux analysis reveals that in Scenario-1 (without insulation), the average heat flux through walls and roofs reaches a peak of 18.6 W/m^2 in June, whereas Scenario-2 (with EPS insulation) reduces it to 5.2 W/m^2, a reduction of nearly 72%. This significant difference translates into approximately 30% energy savings during peak cooling months. To validate the findings, the simulated heat loss data were compared with previous studies [32]. Compared to traditional insulating materials, EPS insulation in this study demonstrates a reduction of 72%, underscoring its superior thermal performance under tropical conditions. Table 9 highlights the alignment of the proposed system's performance with established benchmarks, showing a reduction of heat loss by 90% for roofs and 47% for walls in residential buildings when EPS is used. Table 9 presented a comparative study about heat losses in different buildings. This comparison validates the study's findings and emphasizes the importance of EPS for energy-efficient construction. However, the heat loss or gain cited in Table 9 having a range from 21 to 90%.

Table 9:

Summary of selected study about heat losses in different buildings.

S. No	Types of building	Additional	Heat loss	Ref.
1.	High-rise apartment	WWR (30 %)	29 %	Beradi et al. [32]
2.	Hospital	WWR (16 %)	22 %	Beradi et al. [32]
3.	Primary school	WWR (35 %)	21 %	Beradi et al. [32]
4.	Warehouse	WWR (0.71 %)	23 %	Beradi et al. [32]
5.	Residential building	Roof	90 %	Present study
6.	Residential building	Wall	47 %	Present study

The thermal insulation provided by EPS contributes to lower cooling loads during summer and reduced heating requirements in winter. This not only enhances energy efficiency but also lowers greenhouse gas emissions by reducing energy consumption.

3.1.4 Practical implications of the research

The findings of this study have substantial practical implications for the construction and energy sectors. The integration of Expanded Polystyrene (EPS) as an insulating material for walls and roofs has demonstrated significant reductions in heat loss – up to 90 % in roofs and 47 % in walls – highlighting its effectiveness in enhancing thermal performance and minimizing energy consumption. These results can directly inform the design and construction of energy-efficient buildings, enabling developers and architects to reduce cooling and heating loads, thereby lowering energy costs for end-users. Additionally, the durability and environmental resistance of EPS make it a reliable choice for both new constructions and retrofitting older structures to meet modern energy efficiency standards.

In manufacturing, the lightweight and moldable properties of EPS allow for its seamless integration into pre-fabricated building components, streamlining the construction process. Moreover, the study's alignment with the Energy Conservation Building Code (ECBC) in India supports its adoption as a standard material for sustainable building practices. EPS's contribution to reducing energy demand also aligns with global sustainability goals by lowering greenhouse gas emissions. To further enhance its practicality, manufacturers could explore recycling and sustainable production processes for EPS to address environmental concerns related to its lifecycle. These applications bridge the gap between academic research and real-world implementation, promoting energy conservation and sustainable development in the construction industry.

4 Conclusions

This study demonstrates that incorporating Expanded Polystyrene (EPS) as an insulating material into residential building envelopes significantly reduces thermal losses, with up to 90 % reduction in roofs and 47 % in walls. By leveraging its low thermal conductivity and durability, EPS enhances the thermal performance of buildings while reducing energy consumption. Numerical simulations using COMSOL Multiphysics and eQUEST validate these findings, highlighting EPS's efficiency in mitigating heat transfer under varying seasonal conditions. In addition to the substantial energy savings, the study establishes the scalability and practicality of EPS for energy-efficient construction, particularly in tropical climates like Ranchi, India. The research also fills a gap in existing literature by addressing the material's long-term performance, including resistance to environmental degradation and its economic viability.

By bridging the gap between theoretical research and real-world applications, this study contributes to advancing sustainable building practices, supporting energy conservation goals, and reducing greenhouse gas emissions. These findings align with the Energy Conservation Building Code (ECBC) guidelines, promoting the adoption of innovative insulating materials in construction. Numerical analysis using the FEM approach was used to explore the extent of influence, using a study of heat transport in various scenarios. First, research is conducted to determine the systematic and most appropriate material coupling for the supporting wall and plaster for the summer and winter seasons. The second scenario identifies cement plaster and EPS-filled blocks as the best options for achieving improved thermal insulation performance. Different environmental circumstances are studied in this scenario. As a result, the following points should be used to summarise the work done:

i. It has been demonstrated (by the second scenario) that adding EPS insulating material to a traditional wall composed of plastering layers and bearing load reduces heat loss from the internal environment by 44 %.

ii. The system has the thermal response measured by microclimate quality criteria in residential buildings which ensures that thermal insulation needs are met in both winter and summer months, as evidenced by the temperature graphs on both inside and outside surfaces.

iii. When the second scenario is compared to the first, adding insulating material (EPS) reduces heat loss by 90 % in the roof and 44 % in the walls of the building, as indicated by the temperature graphs on both inside and outside surfaces.

iv. The room inlet air temperature is by average 1.4 °C lower for 7 h during the daytime for ventilation compared to the normal walls.

5 Limitations & future scopes

This study is focused on the climatic conditions of Ranchi, India, which may limit the applicability of the findings to other regions with different environmental conditions, such as arid or polar zones. The material selection was based on the availability of locally accessible resources, such as EPS blocks and cement plaster, which might constrain the replicability of this approach in areas where these materials are unavailable. Furthermore, the simulation models employed simplified assumptions, including uniform wind speeds and solar irradiance, which may not accurately capture the complexities of real-world environmental variations. While the study highlights the thermal efficiency of EPS, it does not include an economic evaluation, such as a detailed cost-benefit analysis, payback period, or lifecycle cost assessment. Additionally, long-term performance factors, such as wear, exposure to moisture, and UV radiation, were not experimentally validated, leaving room for future studies to include durability testing and field validation under varying conditions. Addressing these limitations in future research could enhance the comprehensiveness and applicability of the findings such as:

i. Future research should investigate alternative insulating materials with similar or superior properties, considering their availability in local markets. Studies could also explore energy performance variations across different climatic zones to generalize the findings.

ii. Considering the life expectancy, life cycle, and maintenance costs of EPS and other materials, future studies should analyze their long-term energy performance and economic viability. Detailed cost analyses, including initial investment, operational savings, and return on investment, are essential to quantify the overall feasibility of these materials in diverse construction scenarios.

iii. Future challenges may include addressing the environmental impact of EPS production and disposal. Research into sustainable production methods, recycling processes, and biodegradable alternatives should be prioritized to align with global sustainability goals. Moreover, adapting EPS-based solutions for extreme climates or high-performance buildings can provide valuable insights for further innovation.

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The corrections made in this section will be reviewed by journal production editor.

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Footnotes

Text Footnotes

CQ9

Research ethics: Not applicable.

Author contributions: ~~Conceptualization, OP, AA, PN, LSB, RC, SS; methodology, OP, AA, PN, LSB, RC, SS; formal analysis, OP, AA, PN, LSB, RC, SS; investigation, OP, AA, PN, LSB, RC, SS; writing~~ Conceptualization, OP, AA, PN, LSB, RC; methodology, OP, AA, PN, LSB, RC; formal analysis, OP, AA, PN, LSB, RC, SS; investigation, OP, AA, PN, LSB, RC; writing~~-~~ – ~~original draft preparation, OP, AA, PN, LSB, RC, SS; writing~~ original draft preparation, OP, AA, PN, LSB, RC; writing~~-~~ – ~~review and editing, SS, AK, MA, SR, KR; supervision, SS, AK, MA, SR, KR; project administration, SS, AK, MA, SR, KR; funding acquisition, SS, AK, MA, SR, KR. All authors have read and agreed to the published version of the manuscript.~~ review and editing, SS, AK, MA, SR, KR; supervision, AK, MA, SR, KR; project administration, AK, MA, SR, KR; funding acquisition, AK, MA, SR, KR. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no competing interests.

Research funding: ~~This work has not received any funding.~~ The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University (KKU) through the Research Group Program Under the Grant Number: (R.G.P.2/552/45).

Data availability: ~~My manuscript has no associate data.~~ All the characterizations, analysis, testing's related work and testing's have solely been responsible by Om Prakash and Asim Ahmad. Additionally, the raw data can be obtained on request from the corresponding authors, Om Prakash and Asim Ahmad.

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