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Comparative Thermal Analysis of Flat Roof and U-Shaped Roof with Different Insulation Material

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Abstract

Building consumes the highest amount of energy across the world. For sustainable and energy-efficient building, proper insulating material is required for the constructions. Proper utilization of insulating material will reduce the energy consumption of the building. Energy-efficient buildings reduce the dependency on external cooling devices, i.e., air conditioning, and hence reduce energy consumption and maintain indoor thermal comfort without much expense. The insulation materials can be chosen based on the climatic condition, building design, etc. This study focuses on the area of Bhilai (21.19°N, 81.35°E), Chhattisgarh. The climate of the Bhilai region is tropical. In summers the temperatures of the city reach up to 45°C. As the major component of the heat gains through the roof, the roof insulation is therefore an effective strategy for thermal comfort improvement. In this study, vetiver grass mats, earthen pots, and cocopeat systems were evaluated as roof insulation materials. Two concrete rooms, each measuring 1 m³, were constructed for the experiments conducted in May and June 2025. Instruments such as an infrared thermometer, pyranometer, and thermocouples were employed to monitor temperature profiles and solar radiation. Comparative analysis revealed that the use of vetiver mat as insulation significantly reduced heat gain compared to an uninsulated roof, and using earthen plate and cocopeat as insulation materials thereby lowered energy consumption.

Keywords
Buildings, Insulation material, Thermal Comfort, Energy consumption, Passive cooling

1. Introduction
The rising ambient temperatures during hot summer are progressively elevating the energy demands for building cooling. Consequently, it is essential to reduce the energy consumption of the building throughout the summer season under excessive heat conditions.to create sustainable structures that will reduce reliance on external cooling devices. Several passive cooling techniques such as cross ventilation, evaporative cooling, earth air heat exchanger, shading and insulations are being used in the houses. The roof is the primary element of the building envelope through which the majority of heat gains occur. Consequently, thermal insulation is a crucial approach for reducing heat gain in buildings. Insulation will diminish heat transfer from the outdoors to the indoors. This will ultimately decrease energy use and carbon emissions.

Biodegradable insulation materials such as rice husk, bamboo straw, mud, leaves and coconut fibres is being used in traditional mud houses from the years. This study incorporates three distinct materials: Vetiver grass mat, earthen plate insulation, and cocopeat insulation, applied to the roof to reduce heat transmission into the building and lower the inside temperature of the room. These materials are composed of natural substances and are biodegradable. Vetiver grass is primarily utilized in desert coolers due to its accessibility and low cost. Earthen pots, constructed from mud or clay, are utilized in many regions for daily household purposes as well as for decoration and construction applications. Cocopeat is essentially a byproduct of coconut, characterized by its lightweight, porous structure, and excellent air retention properties (Figure 1).

a b c

Figure 1. (a) Vetiver grass mat (b) Earthen plates (c) Cocopeat

Table 1. Cocopeat thermal properties

Properties	**Value**
Thermal Conductivity (W/m-k)	0.05
Thermal Resistance (m^2-K/W)	0.50
Density (Kg/m^3)	180

Numerous researchers have focused on the reduction of heat from various components of buildings. The primary source of heat gain in the building is the roof, with around 50-70% of heat transfer occurring through it (Rawat & Singh, 2022; Prakash, 2015).

Xu et al. (2024) reported that the application of reflective coating on roofs can decrease surface temperatures by 1.4 to 4.7 °C. Singh, and Buddhi (2022) indicated that the incorporation of phase change materials (PCM) on roofs leads to a reduction in temperature. Augmenting the thickness of insulation materials diminishes heat transfer; but, above a certain ideal threshold, it simply escalates costs without enhancing thermal performance (Saleem et al., 2024; Verma & Rakshit, 2023). Chandra et al. 2020 reported that roof panel with bamboo as an insulation material reduces the indoor temperature of room. Permpituck, & Namprakai, (2012) stated that the energy consumption of the building can be reduced by installing a roof lawn on the building. Researchers address common insulating materials such as phase change materials (PCM), cool roofs, green roofs, expanded polystyrene, and bio composite fibers. The types of insulation materials, their thickness, thermal characteristics, and placement are crucial for assessing the thermal performance of roof insulation Yang et al. 2020.

The aim of this study is to lower the indoor temperature of the room and to evaluate the effectiveness of Vetiver grass mats, earthen plate insulation (Table 1 and Table 2), and cocopeat insulation materials on the roof. Two model houses, one with a flat roof and the other with a U-shaped roof, are made for analysis.

2. Methodology

Figure 2 displays the onsite pictures of two prototype rooms: one with a flat roof and the other with a U-shaped roof, constructed for experimental purposes. Figure 3 illustrates the schematic diagram of the rooms and the positions of the sensors during the experimental operation. Sensors have been installed both inside and outside the space to measure interior and outdoor temperatures. A thermos-hygrometer measures temperature and humidity. The experiment is conducted in the first week of May 2025 and the third week of June 2025, employing the setup to record hourly data for different insulation materials.

Figure 2. On Site images of two rooms with flat and inverted U shaped roof

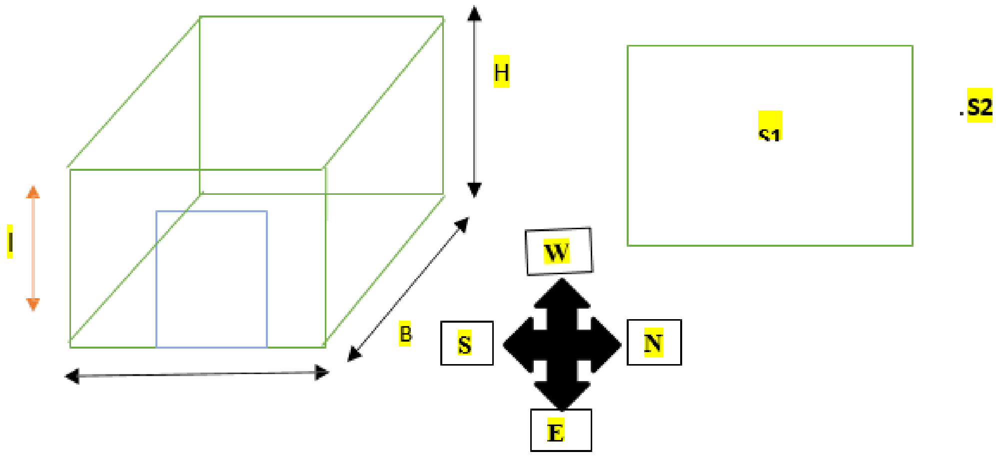

Figure 3. Three dimensional view of room and position of sensors

Table 2. Thickness of insulation

Thickness of insulation (in mm)	Value(mm)
VETIVER MAT	10
EARTHEN PLATE	45
COCOPEAT	25

3. Results and Discussions

Results of the experiment and simulation based on the mathematical formulation for heat transmission from the external environment to the inside of the room. The simulation results for room temperature in a structure built with standard brick are presented initially. The study is subsequently expanded to include rooms created with various insulation materials on roofs.

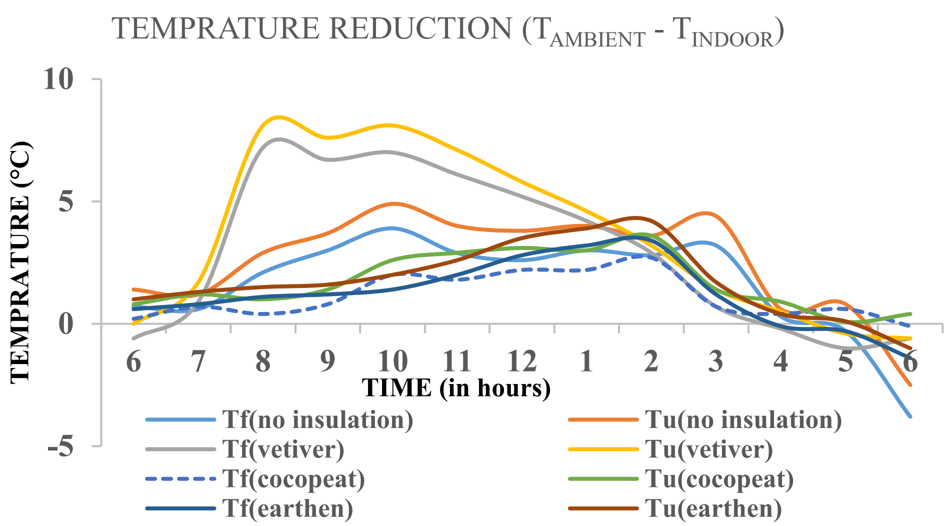

Figure 4 shows the variation of reduction of temperature with respect to time

Figure 4 illustrates the fluctuation in temperature reduction with time, with Tu(vetiver) (U-roof with vetiver) and Tf(vetiver) (Flat roof with vetiver) exhibiting the greatest ΔT, reaching a maximum of approximately 8–9°C at midday. Vetiver offers superior thermal insulation. U-roofs exhibit superior performance relative to flat roofs when both are equipped with identical insulation, as the solar radiation incident on the flat surface is greater, and that on the U surface is lower due to greater reflection.

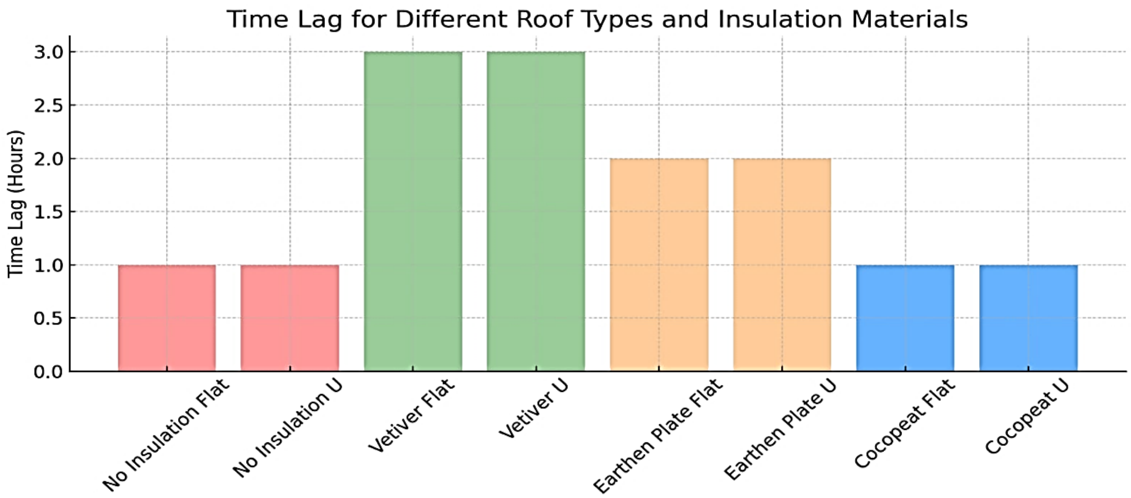

Figure 5. Time lag for different insulations

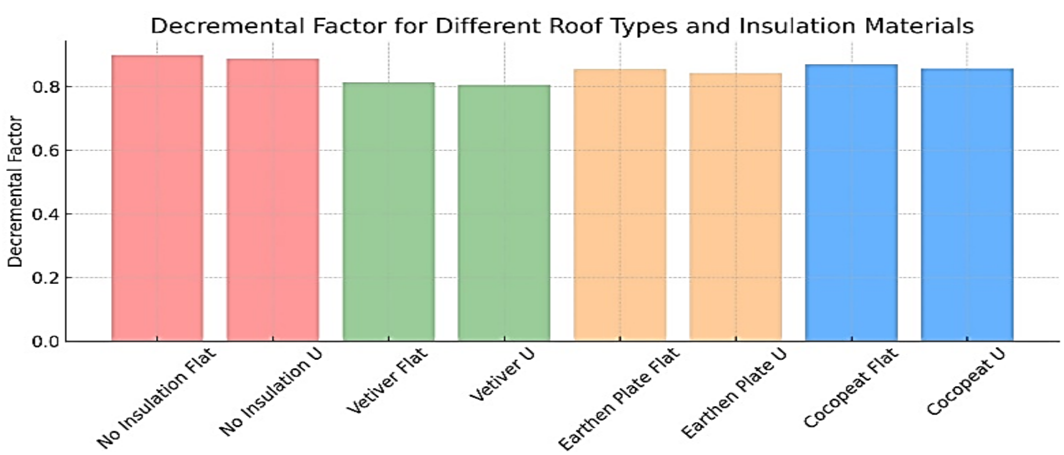

Figure 6. Decremental factor for different insulations

The time lag is the difference between the maximum outdoor and indoor temperatures, and the decrement factor is the ratio of the indoor to outdoor temperature amplitudes. A high time lag and a low decrement factor are preferable for the building. Vetiver insulation (both Flat and U roof) exhibits a maximum time lag of 3 hours as shown in Figure 5 and Figure 6. This indicates it most effectively postpones indoor heat accumulation, hence maintaining colder interiors for an extended period. Vetiver insulation offers superior thermal delay, effectively preserving cooler interiors during peak heat hours. In contrast, Cocopeat insulation and no insulation exhibit a one-hour time lag, signifying negligible delay in heat transfer. No insulation on flat and U-shaped roofs exhibits the highest thermal transmittance values (~0.9), signifying minimal thermal resistance, which allows the majority of external heat to get indoors. Vetiver insulation exhibits the lowest decrement factor (~0.81), indicating its superior capacity to drastically diminish indoor temperature fluctuations as shown in fig 6.Vetiver offers exceptional insulation in terms of time lag and decrement factor, rendering it the most efficient material of the three.

Mathematical model is also developed using energy balance equation of the room (Chel & Tiwari 2009) to validate the experimental results, Figures 7 and 8 illustrate the comparison between the experimental values obtained and those derived from mathematical modelling conducted in Python for flat and U-shaped roofs without insulation.

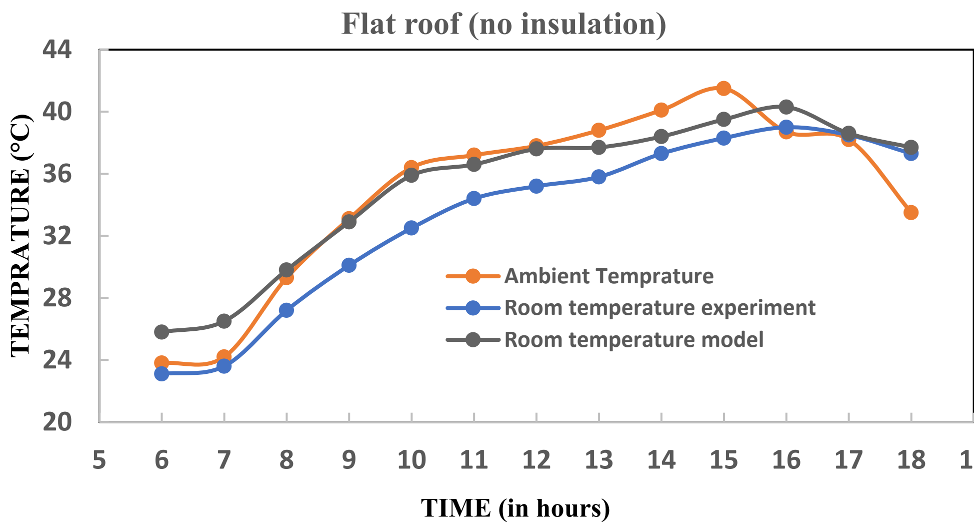

Figure 7. Comparison for flat roof without insulation

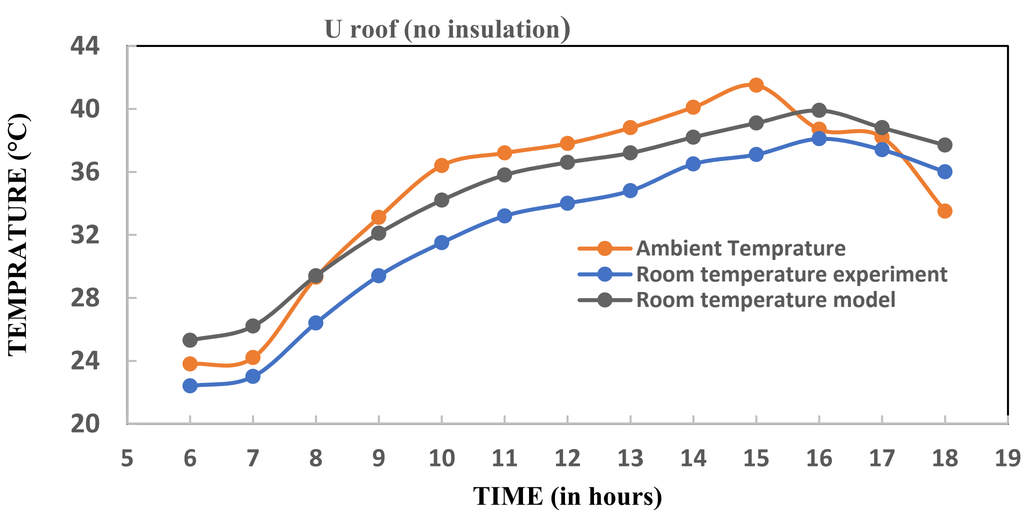

Figure 8. Comparison for U roof without insulation

Figure 9 and Figure 10 show the comparison between the values obtained through experiment performed and its mathematical modeling i.e performed on python for flat and U shaped roof with Vetiver insulation.

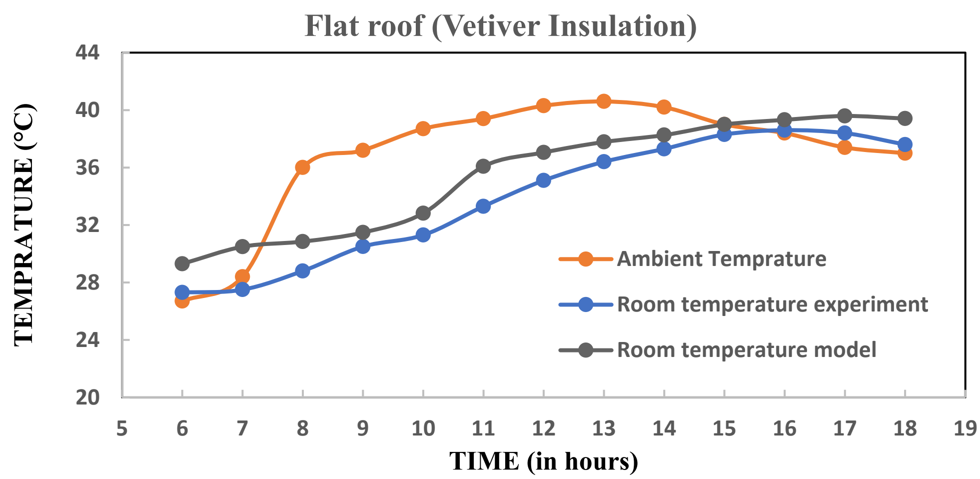

Figure 9. Comparison for flat roof with Vetiver insulation

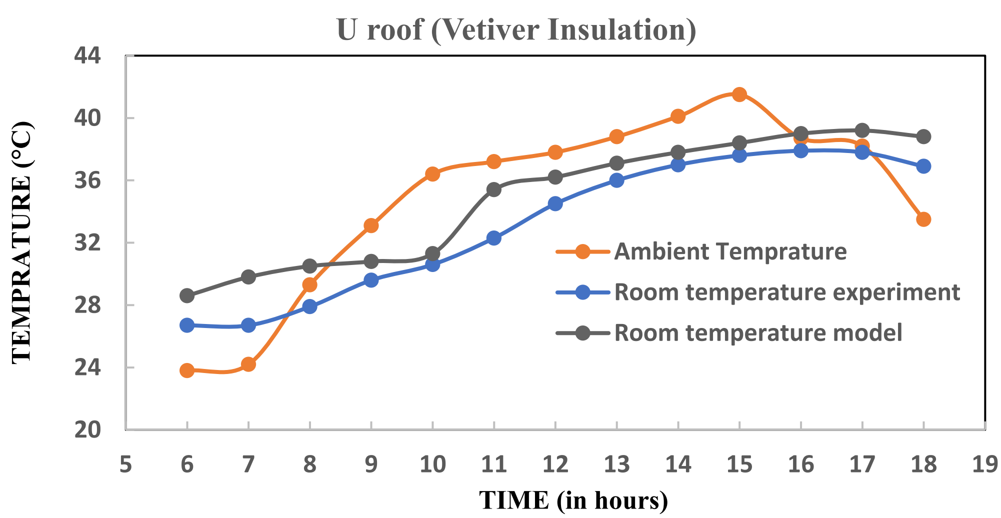

Figure 10. Comparison for U roof with Vetiver insulation

4. Conclusions

- ❖ Vetiver flat roof and U roof exhibits the largest ΔT, reaching approximately 8–9°C at midday. Vetiver offers superior thermal insulation. U-roofs exhibit superior performance relative to flat roofs when both are equipped with identical insulation.
- ❖ Vetiver insulation (both Flat and U roof) exhibits a maximum time lag of 3 hours. This indicates that it most effectively postpones indoor heat accumulation, hence maintaining cooler interior temperatures for an extended period. Vetiver insulation offers optimal thermal delay, aiding in the preservation of cooler interiors during peak heat hours.
- ❖ Vetiver insulation exhibits the lowest decremental factor (~0.81), indicating its superior efficacy in greatly diminishing the amplitude of indoor temperature fluctuations.
- ❖ The Inverted U Roof incurs a greater base construction cost (₹5128) than the Flat Roof (₹4800), mainly because to its elevated roof structure expenses.

- Among the three for both roofing kinds. Cocopeat is positioned between Vetiver and Earthen Plate regarding price. If affordability is the primary concern, Vetiver insulation on a flat roof is the most economical option.

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Biographies

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