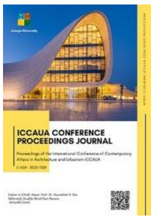

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Incorporation of Phase Change Materials for Thermal Comfort in Buildings: A Case of Warm and Humid Climate

*** [1] Paras Jain , [2] Abhijeet Pal , [3] Prabhleen Kaur , [4] Reetwik Mukherji**
[1,] Thapar Institute of Engineering & Technology, Patiala, Punjab,India
[2 & 3] MBS School of Planning & Architecture, GGSIPU University, New Delhi, India
[4,] Manipal School of Architecture & Planning, MAHE, Manipal, India
[1]E-mail:jainparas9898@gmail.com,[2]E-mail:abhijeetpal1706@gmail.com,[3]E-mail:prabhleenkaurwork@gmail.com,[4]E-mail:mukherjireetwik@gmail.com

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Abstract

Thermal comfort in warm–humid climates remains challenging due to persistently high temperatures, elevated humidity, and limited night-time cooling. Conventional mechanical cooling increases energy demand, highlighting the need for passive, climate-responsive alternatives. This research investigates the potential of Phase Change Materials (PCMs) and, more specifically, Phase Change Humidity Control Materials (PCHCMs) as an integrated hygrothermal regulation strategy for buildings in warm–humid Indian conditions. PCHCMs uniquely moderate both temperature and relative humidity by simultaneously exchanging sensible and latent heat, thereby influencing building energy loads. The study compares conventional wall assembly to PCHCM infused wall assembly with diatomite , gypsum and hempcrete as hygroscopic matrices within the PCHCM. The study also looks forward to identifying an optimal composite of PCHCM infused wall assembly by microencapsulation , macroencapsulation or shape-stabilized PCMs . Using Künzel's HAMT (Heat–Air–Moisture Transport) model, the research simulates the behavior of the developed composite within the building envelope through DesignBuilder. The findings aim to advance passive material technologies that improve indoor comfort while reducing cooling energy consumption in warm–humid climates.

Keywords: PCM; Phase change humidity control material; Hygroscopic material; Thermal comfort; HAMT Model; Energy saving simulation.

1. Introduction

Thermal comfort in warm–humid climates remains a persistent challenge due to the simultaneous presence of high ambient temperatures, elevated relative humidity, and limited nocturnal cooling, all of which intensify occupant discomfort and increase dependence on energy-intensive mechanical cooling systems. In rapidly urbanizing countries such as India, where cooling demand continues to rise, the development of passive, climate-responsive building materials has become increasingly critical. Phase Change Materials (PCMs) have emerged as promising thermal energy storage materials due to their ability to absorb and release substantial amounts of latent heat during phase transitions, thereby moderating indoor temperature fluctuations without external energy input.

However, conventional PCMs primarily address sensible heat regulation and remain limited in warm–humid environments where moisture-driven discomfort plays an equally significant role. To overcome this limitation, Phase Change Humidity Control Materials (PCHCMs) have been developed as advanced composite materials that integrate PCMs with hygroscopic substrates, enabling simultaneous regulation of both temperature and indoor humidity through coupled heat and moisture exchange. This dual hygrothermal buffering capability makes PCHCMs particularly relevant for tropical and humid climates, where latent cooling loads often rival or exceed sensible cooling demands. In this context, the present study investigates the performance of capric acid, a bio-based organic PCM selected for its favorable phase change temperature and thermal storage characteristics, in combination with four hygroscopic materials to develop optimized PCHCM composites for Indian warm–humid climatic conditions. Using hygrothermal simulation through Künzel's Heat–Air–Moisture Transport (HAMT) model in DesignBuilder, the research evaluates the effectiveness of these composites in improving indoor thermal comfort and reducing cooling energy demand, while identifying the most suitable material configuration for climate-responsive building envelope applications.

2. Literature Review

2.1 Thermal Comfort Challenges in Warm–Humid Indian Climates

Thermal comfort in warm–humid climates is difficult to achieve because occupants are affected not only by high air temperature but also by high relative humidity, low wind movement, and limited night-time cooling. In the Indian context, warm–humid zones such as Kerala, Tamil Nadu, Andhra Pradesh, West Bengal, and coastal regions experience average temperatures of 25–35°C, relative humidity often above 70–80%, and low diurnal temperature variation. These conditions create a combined sensible and latent heat load, where the body's natural evaporative cooling mechanism becomes less effective. As a result, buildings in such climates often depend heavily on mechanical cooling and dehumidification.

2.2 Phase Change Materials in Building Applications

Phase Change Materials (PCMs) are thermal energy storage materials that absorb and release heat during phase transition, usually from solid to liquid and liquid to solid. Unlike conventional materials that store heat through sensible heat, PCMs store energy through latent heat, allowing them to absorb large amounts of heat at nearly constant temperature. This makes them useful in building envelopes because they can delay indoor temperature rise, reduce peak heat gain, and improve thermal stability.

PCMs have been widely studied in walls, roofs, ceilings, floors, and wallboards. They can reduce indoor temperature fluctuations, shift peak cooling loads, and lower dependence on air-conditioning. However, their performance depends strongly on correct material selection, melting temperature, latent heat capacity, thermal conductivity, compatibility with the host material, and method of integration.

2.3 Integration of PCM in Building Envelopes

PCM can be integrated into building envelopes through three major methods: direct incorporation, encapsulation, and shape-stabilized/form-stable composites.

- Direct incorporation is simple but can cause leakage and compatibility issues.
- Microencapsulation prevents leakage by enclosing PCM particles in small protective shells, making it suitable for plasters, wallboards, coatings, and composite panels.
- Macroencapsulation uses larger containers such as panels, tubes, or pouches and is easier to replace or retrofit.
- Shape-stabilized PCM embeds the PCM into a porous or polymer matrix, preventing leakage while allowing the material to retain its form during melting

2.4 Capric Acid as a Suitable PCM for Warm–Humid Building Envelopes

Capric acid is an organic fatty-acid PCM and is suitable for building applications because of its relatively stable phase-change behavior, non-corrosive nature, biodegradability, and good latent heat storage potential. Fatty acids such as capric acid, stearic acid, and palmitic acid are often preferred over salt hydrates because they show better chemical stability and reduced phase segregation issues.

Sivasubramani P. A. and Srisanthi V. G. specifically evaluated capric acid as a PCM in building walls using DesignBuilder simulation. Their study found that incorporating capric acid into wall materials improved thermal comfort hours by at least 6.5% and achieved a minimum of 15% energy savings, while also performing better than EPS in extending comfort hours.

2.5 Hygroscopic Materials for Moisture Regulation

Since warm–humid climates are affected by both temperature and moisture, hygroscopic materials become important. Hygroscopic materials absorb and release moisture depending on indoor relative humidity, helping stabilize indoor humidity fluctuations. In your study, four hygroscopic matrices are selected: diatomite, gypsum, hempcrete, and hemplime.

- Diatomite is a porous natural mineral with strong moisture adsorption potential due to its pore structure. Zhang et al. note that natural porous minerals such as zeolite, diatomite, bentonite, and sepiolite can adsorb water molecules through their pore structures, and diatomite can adsorb water content up to about 10% at 80% RH.
- Gypsum is widely used in building boards and interior surfaces and has moderate moisture-buffering ability. Zhang et al. list gypsum board among traditional building materials tested for water-vapor sorption, making it relevant as a practical and conventional comparison material.
- Hempcrete and hemplime are bio-based porous materials with strong hygrothermal potential. Hemp fibers are hydrophilic due to their plant-based cellular structure, allowing them to absorb moisture under humid conditions. Zhang et al. also identify hemp fiber among natural plant fibers with high moisture absorption capacity, making it suitable for humidity-regulating composites.

2.6 Coupling PCM with Hygroscopic Materials: PCHCM

Phase Change Humidity Control Materials (PCHCMs) combine two functions: the PCM component regulates temperature through latent heat storage, while the hygroscopic component regulates humidity through moisture adsorption and desorption. This makes PCHCM more suitable than conventional PCM in warm–humid climates because it addresses both sensible and latent loads.

In a PCHCM wall system, capric acid can absorb heat during peak indoor temperatures, while materials such as diatomite, gypsum, hempcrete, or hemplime can buffer indoor humidity. This coupling can reduce temperature swings, stabilize relative humidity, improve indoor comfort, and potentially reduce cooling and dehumidification loads.

2.7 Integration of PCHCM in Wall Assemblies

The integration of PCHCM into wall assemblies can be achieved through microencapsulation, macroencapsulation, or shape-stabilized composite formation. For organic PCMs such as capric acid, encapsulation is especially important

because it prevents leakage during melting and improves compatibility with building materials. Shape-stabilized systems are also suitable because the PCM is retained within a porous support matrix, such as diatomite or hemp-based composites Existing literature shows that PCMs can reduce indoor temperature fluctuations, while hygroscopic materials can regulate indoor humidity. However, most PCM studies focus only on thermal performance, and most humidity-buffering studies focus only on moisture regulation. Limited research has evaluated capric-acid-based PCHCM systems in Indian warm–humid climatic conditions, especially by comparing different hygroscopic matrices within the same wall assembly.
Therefore, this research addresses the gap by simulating capric acid with diatomite, gypsum, hempcrete, and hemplime to identify the most effective PCHCM composite for improving indoor thermal comfort and reducing cooling energy demand in Indian humid climates.

3. Methodology

This study adopts a simulation-based comparative methodology to evaluate the hygrothermal performance of capric-acid-based Phase Change Humidity Control Materials (PCHCMs) integrated within building wall assemblies for warm–humid Indian climatic conditions.
The methodology is structured in six sequential stages:

Stage 1: Problem Identification and Climate Context

The study begins by identifying the thermal comfort challenges associated with warm–humid Indian climates, characterized by elevated ambient temperatures, high relative humidity, and limited nocturnal cooling. These climatic conditions result in increased cooling energy demand and occupant discomfort, highlighting the need for passive hygrothermal regulation strategies. A literature review is conducted to establish:

- thermal comfort requirements in warm–humid climates
- limitations of conventional PCM systems
- relevance of hygroscopic materials for humidity buffering
- potential of PCHCM as a dual heat-moisture control strategy

Stage 2: Material Selection

Based on literature-backed thermal and hygrothermal performance criteria, the material components are selected.

Phase Change Material

Capric Acid is selected as the base PCM due to:

- suitable phase change temperature for building comfort applications
- high latent heat storage capacity
- chemical stability
- biodegradability
- non-corrosive behavior
- compatibility with building envelope applications

Hygroscopic Materials

Four hygroscopic materials are selected for comparative evaluation:

Diatomite

- high porosity
- strong moisture adsorption
- lightweight mineral structure

Gypsum

- conventional building compatibility
- moderate moisture buffering
- ease of integration

Hempcrete

- bio-based porous structure
- strong moisture regulation
- thermal insulation properties

Stage 3: Development of Wall Assembly Configurations

Multiple wall assembly cases are developed to compare the influence of PCM and PCHCM integration.
Simulation cases include:

Base Case: Conventional clay brick wall assembly without PCM
Case 1 Clay brick wall + Capric Acid PCM
Case 2 Clay brick wall + Capric Acid PCM + Diatomite
Case 3 Clay brick wall + Capric Acid PCM + Gypsum
Case 4 Clay brick wall + Capric Acid PCM + Hempcrete

This comparative framework allows isolation of thermal-only PCM effects versus combined hygrothermal PCHCM effects.

Stage 4: Simulation Model Development

A simulation model is developed in **DesignBuilder** using the **Künzel HAMT (Heat-Air-Moisture Transport) model** to simulate coupled thermal and moisture behavior.

Stage 5: Hygrothermal Performance Simulation

Each wall assembly is simulated under identical climatic and occupancy conditions.
Performance evaluation focuses on:

Thermal Parameters

- indoor operative temperature
- peak indoor temperature reduction
- temperature fluctuation damping
- thermal lag/time delay
- latent heat storage effectiveness

Moisture Parameters

- indoor relative humidity variation
- moisture adsorption/desorption response
- humidity buffering capacity

Energy Performance

- cooling load reduction
- passive energy savings
- HVAC demand reduction

This stage quantifies the performance difference between conventional PCM systems and PCHCM-integrated systems.

Stage 6: Comparative Analysis and Optimization

Simulation outputs are comparatively analyzed to identify the most effective hygroscopic composite.
Comparison criteria:

- Operative Temperature
- Relative Humidity
- Wall Heat Transfer through Building Envelope
- Monthly Indoor Air Temperature Variation

The best-performing capric-acid-based PCHCM configuration is identified as the optimized passive wall assembly for warm–humid Indian climates.

4. Simulation Parameters

4.1 Building Model Parameters

Simulation model characteristics:

- Location: Pune, India
- Climate type: warm–humid representative condition
- Room dimensions: 4 m × 3 m × 3 m
- Window-to-wall ratio: 25%
- Occupancy density: 0.8 persons/m²
- Weekday operational schedule: 18:00–06:00
- Weekend schedule: 24-hour occupancy

The model simulates indoor thermal behavior under realistic occupancy and climatic exposure.

Activity:

The occupancy schedule was set up through DesignBuilder using a Compact Schedule with year-round constant occupancy ("Through: 31 Dec; For: AllDays; Until: 24:00, 1").A residential activity template called TM59_SingleBedroom was used to simulate a residential bedroom according to the TM59 residential comfort criteria. The occupancy density was defined as 0.08 people/m², and the zone was modeled in both thermal and daylight analysis.The heating and cooling setpoint values were set to 18°C and 25°C, respectively, and the relative humidity limit ranged from 10% to 90%. The heat gains from the computer and office equipment were switched off.

Construction:

A medium-weight construction template with insulation was used for modeling in this simulation framework. The simulation was done in such a way that the parameters remained unchanged among all the simulations except the configuration of the external walls. For the evaluation of thermal and moisture performance for various construction materials like PCM, hempcrete, diatomite, gypsum, and insulating materials, only external wall configurations were changed.

The roof of the building was made from the flat roof design with a U-value of 0.25 W/m²K to reduce heat gain in a warm and humid climatic condition prevalent in Pune city. The construction of the ground floor was made up of 200 mm thick concrete slab while the internal floors and walls were created with 100 mm thick concrete slab. Similarly, both the internal and external doors of the building were made up of wooden doors.

Glazing:

For the glazing setup in the simulation, it was assumed that there would be a single layer of clear glazing without any external shading, thereby providing an equal level of solar radiation for all simulation models. A 6 mm thickness of clear glass was provided to the outer surface of the windows to permit daylighting and study the thermal performance of the wall sections due to solar radiation.The windows had a window-to-wall ratio of 25%, while the standard window height is 1.5 meters. The window sill height is 0.8 meters. There were no external shades or outside reveals provided in the simulation setup**.**

HVAC/Ventilation:

The HVAC system that was utilized within the model is of type Fan Coil Unit (4-Pipe) with an air-cooled chiller. The heating source was selected as natural gas with a seasonal CoP of 0.85, while the cooling energy source was grid electricity with a seasonal CoP of 1.80.The mechanical ventilation option was switched off, but natural ventilation was on with an outdoor air rate of 5 ACH (Air Changes per Hour). This choice is based on the fact that the climate zone of Pune requires mixed-mode simulation in which both natural ventilation and HVAC can interact. This HVAC system schedule was tied up to the TM59 Residential Occupancy Schedule in order to make its operation realistic and check thermal performance under occupied conditions.

4.2 Simulation Cases

4.2.1 Base Case

Figure 1. Conventional clay brick wall assembly without PCM.

4.2.2 Case 1

Figure 2. Clay brick wall with Capric Acid PCM.

4.2.3 Case 2

Figure 3. Clay brick wall + Capric Acid PCM + Diatomite.

4.2.4 Case 3

Figure 4. Clay brick wall + Capric Acid PCM + Gypsum.

4.2.5 Case 4

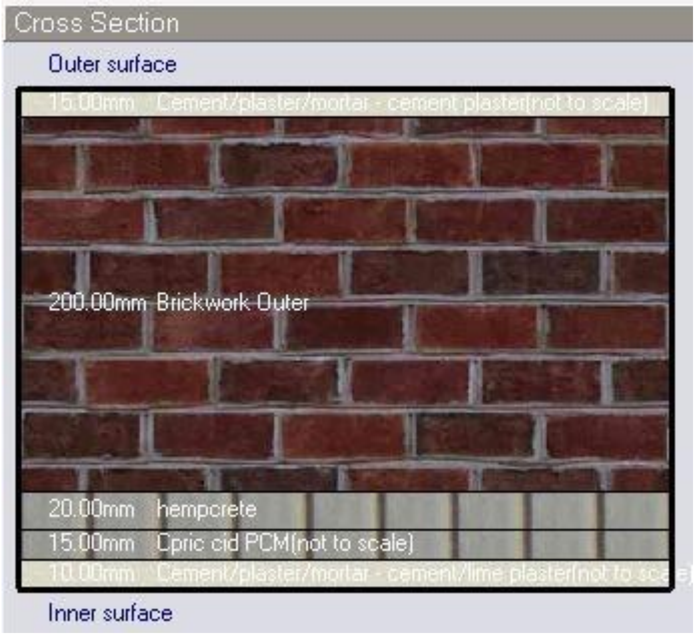

Figure 5. Clay brick wall + Capric Acid PCM + Hempcrete.

5. Simulation Result

The best-performing capric-acid-based PCHCM configuration is identified as the optimized passive wall assembly for warm–humid Indian climates on the basis of :

A. Operative Temperature

Operative temperature can be viewed as the result of both the air temperature indoors and the mean radiant temperature and is an essential indicator for evaluating thermal comfort conditions.

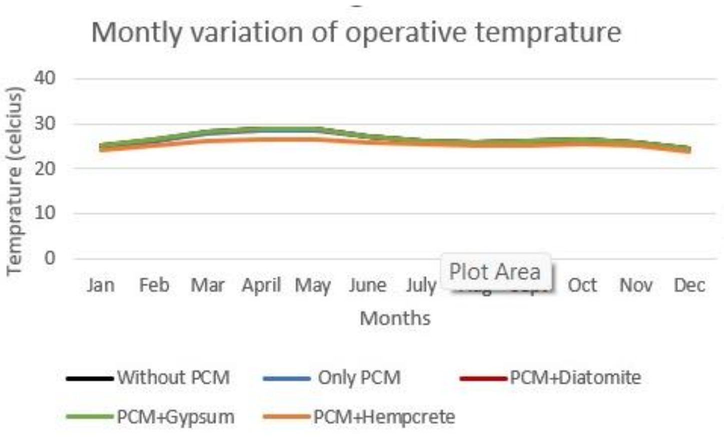

Figure 6. Operative Temperature.

In summer months, the "Without PCM" wall structure registered the highest values of operative temperatures, suggesting greater indoor discomfort.In contrast to other materials, the use of PCM decreased the highest peak values slightly by storing latent heat.

PCM + Diatomite and PCM + Gypsum exhibited better heat stabilization as well as reduced temperature fluctuations, thanks to higher thermal mass.The wall made of PCM and hempcrete proved to have the lowest values of operative temperature all year round.High thermal mass of hempcrete, which has high porosity and moisture absorbency, together with heat storage capacity of PCM makes an ideal thermal environment indoors.

B. Relative Humidity

Relative humidity indoors becomes an important factor in hot and humid climatic regions, since high relative humidity decreases comfort and causes discomfort.There was an increase in relative humidity during monsoon and late summer seasons (June to October). Without PCM wall system exhibited maximum indoor humidity level. Only PCM had marginal impact on controlling relative humidity. PCM along with diatomite and gypsum exhibited relatively better performance regarding moisture regulation. The wall system with PCM and hempcrete exhibited minimum levels of indoor relative humidity. Interpretation

Hempcrete can be described as a moisture buffering material which can absorb and emit moisture depending upon external environment.The addition of PCM helped achieve greater balance through reduction in thermal fluctuation resulting in humidity fluctuation.Use of PCM along with hempcrete can be considered ideal for hot and humid climatic region because of its superior moisture buffering property.

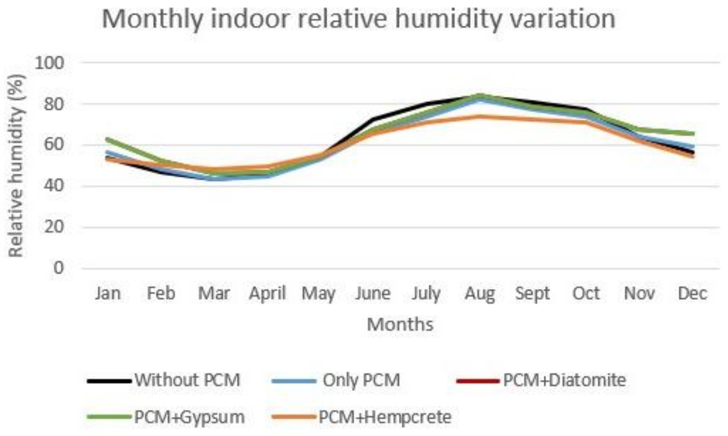

Figure 7. Relative Humidity.

C. Wall Heat Transfer through Building Envelope

There was an increase in heat transfer during the hottest months (March–May).The Without PCM wall system was characterized by quick heat infiltration since its thermal energy storage capability was relatively low.Introducing PCM enhanced heat storage and delayed heat flow.Combination of PCM with Diatomite and PCM with Gypsum provided high thermal energy storage capability and delayed thermal energy transfer.The PCM + Hempcrete combination had the highest thermal energy storage capability of all mixes.

Hempcrete is used as a thermal buffer because of low thermal conductivity,high moisture buffering capacity and delayed heat transmission.With the use of PCM, the wall system efficiently blocked heat transfer through the building enclosure.

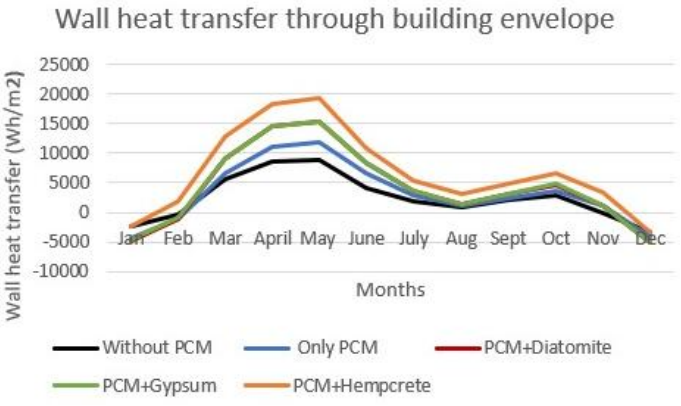

Figure 8. Wall Heat Transfer.

D. Monthly Indoor Air Temperature Variation

Indoor air temperature has a direct effect on comfort level and cooling load.The "Without PCM" wall paneling exhibited the highest indoor temperatures during summer months. PCM alone helped reduce peak indoor temperatures marginally owing to its ability to absorb latent heat of phase change. The "PCM + Diatomite" and "PCM + Gypsum" wall panels had stable indoor temperatures; however, fluctuations were noticeable. The "PCM + Hempcrete" wall paneling demonstrated the lowest indoor temperatures at all times.InteThe inclusion of hempcrete enhanced the insulation and moisture properties, whereas the addition of PCM prevented heat gain during the day.

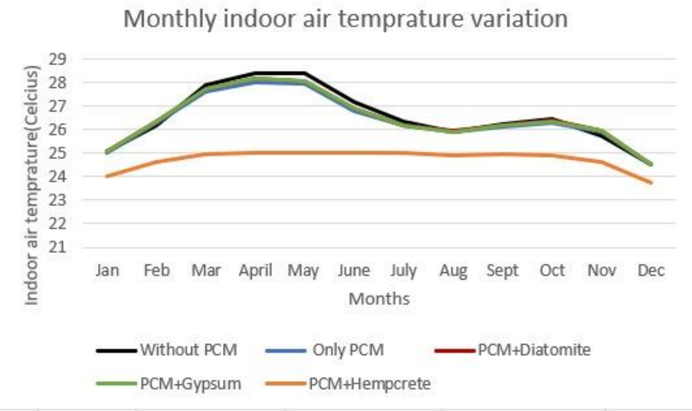

Figure 9. Indoor Air Temperature.

5. Discussion

The study analyzed the thermal performance of different wall assemblies incorporating PCM, diatomite, gypsum, and hempcrete under hot and humid climatic conditions using HAMT-E simulation in DesignBuilder.

- The results clearly indicate that the incorporation of PCM improved the thermal storage capacity of the wall system by absorbing excess heat during peak daytime conditions and releasing it gradually during cooler periods. This reduced sudden indoor temperature fluctuations and improved thermal stability.
- The Without PCM wall assembly consistently showed higher operative temperature,higher indoor air temperature,greater heat penetration through the building envelope and poorer humidity regulation.This indicates that conventional wall systems are less effective in resisting heat gain in tropical climates.
- The Only PCM wall assembly demonstrated moderate improvement in thermal performance. The phase change material reduced peak temperature rise due to latent heat storage; however, the absence of a hygroscopic layer limited its ability to regulate indoor humidity and long-term thermal stability.
- The incorporation of diatomite with PCM improved the thermal inertia of the wall system. Diatomite enhanced heat absorption and delayed thermal transmission through the building envelope due to its porous structure and thermal storage capability. This resulted in lower indoor temperature fluctuations,delayed heat gain and improved thermal lag.
- The PCM + Gypsum wall assembly showed similar behavior to the diatomite configuration. Gypsum improved thermal mass and contributed to better heat storage characteristics. However, its moisture-buffering capability was lower compared to hempcrete, limiting its effectiveness in highly humid climatic conditions.
- Among all tested configurations, the PCM + Hempcrete wall assembly exhibited the best overall thermal and hygrothermal performance throughout the year.
- The superior performance of hempcrete can be attributed to its low thermal conductivity,porous internal structure,hygroscopic behavior, moisture-buffering capacity and high thermal resistance.
- Hempcrete effectively absorbed and released moisture depending on surrounding environmental conditions, thereby maintaining more balanced indoor relative humidity levels. This characteristic is extremely beneficial in hot and humid climates where excess moisture significantly affects occupant comfort. The integration of PCM with hempcrete created a synergistic effect:
- PCM controlled heat storage and thermal regulation while hempcrete controlled both heat and moisture transfer.
- The operative temperature analysis showed that the PCM + Hempcrete configuration maintained the lowest temperature values during peak summer months, indicating superior indoor thermal comfort conditions.
- The indoor air temperature graph demonstrated that PCM + Hempcrete consistently maintained temperatures close to the comfort range throughout the year, minimizing overheating during summer months.
- The wall heat transfer analysis confirmed that the PCM + Hempcrete wall assembly significantly delayed and reduced heat transmission through the building envelope, thereby improving passive cooling performance.
- The indoor relative humidity analysis further validated the effectiveness of hempcrete as a hygroscopic material. Compared to all other configurations, PCM + Hempcrete maintained lower and more stable indoor humidity levels during monsoon and humid periods.
- The results collectively indicate that the use of hygroscopic materials along with PCM can significantly improve the passive thermal performance of buildings in tropical climates.
- The study also demonstrates that combining latent heat storage materials (PCM), thermal mass enhancement materials and hygroscopic materials can effectively reduce dependence on mechanical cooling systems.
- From a sustainability perspective, hempcrete additionally offers low embodied energy,carbon sequestration potential,lightweight construction and eco-friendly material characteristics, making it a highly suitable material for climate-responsive building design.

- Overall, the research confirms that the Clay Brick + PCM (Capric Acid) + Hempcrete + Plaster wall assembly is the most effective configuration among all tested cases for hot and humid climatic regions of India.The proposed wall assembly provides improved thermal comfort,reduced indoor overheating,better humidity regulation,enhanced thermal stability,lower heat transfer and improved passive cooling performance.

Therefore, the integration of PCM with hempcrete can be considered a highly efficient and sustainable strategy for future energy-efficient residential construction in tropical and humid climatic regions.

6.Conclusions

This study demonstrates that integrating PCM with hygroscopic materials can significantly improve indoor thermal comfort and energy performance in hot and humid climates.The simulation results indicate that the PCM + Hempcrete wall assembly outperformed all other wall configurations in terms of:thermal comfort,indoor temperature reduction,heat transfer resistance,and humidity control.

The hygroscopic behavior of hempcrete combined with the latent heat storage capability of PCM created a highly efficient passive cooling system suitable for Indian climatic conditions.

Therefore, the Clay Brick + PCM (Capric Acid) + Hempcrete + Plaster wall assembly can be considered the most effective and sustainable solution for residential buildings in hot and humid regions of India due to its:

superior thermal performance,passive cooling capability,reduced overheating,and improved indoor environmental quality

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Conflicts of Interest

“The author(s) report no conflicts of interest.”

Data Availability Statement

The data supporting the findings of this study are available within the article. Additional simulation data may be obtained from the corresponding author upon reasonable request.

Institutional Review Board Statement

Not applicable. This study did not involve human participants, animals, clinical data, or any research requiring ethical approval or Institutional Review Board (IRB) review.

CRediT Author Statement

“All authors have read and approved the final manuscript.”

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