IJESDS Vol: 1(2): 373-383, 2026
https://doi.org/10.68086/JYAV9147

https://ijesds.org

International Journal of Environmental Sciences, Development & Sustainability
An official publication of the
Faculty of Environmental Sciences
Open Access | Peer-reviewed | International
ISSN (Online): 3156-4461

RESEARCH ARTICLE

Surface Reflectivity Impacts on Thermal Perception and Cooling Energy in Buildings

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ABSTRACT

Building materials and their properties, such as surface color and reflectivity, play a critical role in indoor thermal conditions, yet their interactions on thermal comfort and energy consumption are still not well understood in many emerging climates. This research explores the effects of surface reflectivity on indoor thermal performance through a numerical simulation model in MATLAB. A dynamic model of heat balance was developed to assess indoor temperature, thermal comfort (predicted mean vote, PMV), and cooling energy demand for a range of reflectivity values (0.2-0.8). The model shows that higher reflectivity results in substantial indoor temperature reduction (2.16-3.0°C), as peak indoor temperatures decrease from 34°C (low reflectivity) to 30°C (high reflectivity). This, in turn, enhances thermal comfort, with PMV values changing from +2.30 (warm discomfort) to about +0.19 (near neutral comfort). The energy analysis reveals that the cooling load is decreased by about 16.27% from nearly 5080 kWh/day (low reflectivity) to 5980 kWh/day (high reflectivity). The results show the impact of surface reflectivity on thermal comfort and energy demand. Finally, the research demonstrates that surface reflectivity is an effective passive cooling technique, especially in warm climates, and has important implications for building design and energy efficiency.

Keywords: *Surface Reflectivity; Thermal Perception; Energy Efficiency; Thermal Comfort; Modelling; Sustainable Building*

1. INTRODUCTION

Indoor environmental quality (IEQ) plays a vital role in sustainable building design, especially in sunny climates where buildings are often exposed to excessive heat gain. Much of the thermal discomfort experienced indoors is due to heat gain from solar radiation transmitted through and absorbed by building envelopes, with the colour and reflectivity of surface materials being an important factor in the heat-gain process (Uriarte et al., 2024; Ziaeemehr et al., 2023). In recent years, there has been a growing focus on passive cooling approaches which minimise the use of air-conditioning equipment, a significant driver of global energy demand and greenhouse gas emissions (Yuan et al., 2024; Zhang et al., 2025). Reflectivity, or albedo, is the proportion of solar radiation reflected by a surface (Monchau, 2024; Synnefa et al., 2005). Surfaces with high reflectivity reflect more solar radiation, which minimises heat absorption and indoor warming (Zhang et al., 2017; Santamouris et al., 2023). In contrast, materials with low reflectivity absorb greater amounts of solar energy, leading to higher indoor heat gain and cooling energy consumption (Li et al., 2013). Research has demonstrated that surface reflectivity adjustment is one of the most efficient passive design measures to reduce building overheating, particularly in hot climates (Santamouris, 2015).

The interaction between materials and indoor thermal conditions relies on basic principles of heat transfer, such as conduction, convection, and radiation (Lv et al., 2022; Zhang et al., 2024). Heat absorbed by building external surfaces is transmitted to indoor environments through building envelopes, thus affecting the indoor thermal environment and occupants' thermal comfort (Hu et al., 2023; Han, 2025). This often involves energy balance calculations, incorporating both heat gains due to solar radiation and heat losses through building envelopes (Incropera et al., 2011). But many traditional studies mostly emphasise temperature reduction without taking into account human thermal comfort and energy consumption together. The most common model used to assess human thermal comfort is the Predicted Mean Vote (PMV) model, which predicts the thermal sensation of occupants based on environmental factors and human physiology (Kim et al., 2025; Frontiers in Built Environment, 2020). Fanger's PMV model is one of the most commonly used models for predicting thermal comfort in buildings (Ze Ze et al., 2024; Maier et al., 2024). However, many building performance studies do not link comfort models with thermal analysis based on building materials, leading to a lack of comprehensive evaluation of indoor comfort (Zhu et al., 2021; Hu et al., 2023).

Computer modeling has recently enhanced thermal building analysis. Software like MATLAB can dynamically model the relationship between solar radiation, material behaviour, indoor temperature, and energy consumption (Simonazzi et al., 2025; Kon et al., 2024). These simulations can efficiently test different design options without the need for expensive experiments and are popular because they can incorporate multiple factors and forecast performance under different conditions (Alghamdi et al., 2024; Luo et al., 2024). While recent studies have made advancements, there remains a need for models that can integrate material reflectivity, indoor thermal comfort, and energy use. Typically, research considers these aspects separately, which makes it difficult to apply to sustainable design. Furthermore, few studies provide a quantitative analysis of the effects of surface reflectivity and color changes on human comfort and energy use under different environmental conditions.

This paper presents a dynamic simulation in MATLAB that integrates solar radiation, indoor thermal performance, indoor comfort (PMV index), and cooling energy demand. This model examines indoor responses to different surface reflectivity levels in different climates to enhance sustainable building design by improving comfort and energy efficiency.

2. MATERIALS AND METHODS

Study Design and Approach

This research uses a computational experimental approach to examine how surface color and reflectivity affect indoor thermal performance and thermal comfort. We developed a physics-based computational model in MATLAB to predict heat transfer, solar heat gain, indoor temperature variations, thermal comfort, and energy consumption under different reflectivity scenarios. This method combines building physics, energy balance, and comfort studies, enabling the ability to test passive design strategies without performing experiments (ASHRAE, 2021; Incropera et al., 2011).

Materials Used

The materials used in this study are categorized as building envelope properties, environmental conditions, and indoor physical parameters.

Building Surface Materials (Reflectivity Levels)

Table 1. Selected four representative surface reflectivity values (NASA, 2021)

Material Type	Reflectivity (ϱ)	Description
Dark surface	0.2	High absorption materials (dark concrete)
Medium-dark surface	0.4	Standard painted surfaces
Light surface	0.6	Light-colored paints, plaster
Highly reflective surface	0.8	Cool roof coatings, reflective paints

Environmental Conditions

Two climatic conditions were modeled, which include:

a) Hot climate scenario: representative of tropical environments with high solar intensity
b) Mild climate scenario**:** moderate temperature and solar exposure

Indoor Space Characteristics

The indoor environment was modeled as a single-zone thermally homogeneous space, defined by parameters such as room volume, Wall Area, Heat Transfer Coefficient, Air Density, and Specific Heat capacity (Incropera et al., 2011).

Conceptual Modelling Framework

The thermal behavior of the indoor environment was modeled as a lumped parameter energy balance system, where heat gains and losses determine the evolution of indoor air temperature over time. This approach is consistent with classical building heat transfer theory (Incropera et al., 2011; ASHRAE, 2021).

Solar Radiation and Material Reflectivity Model

Incident Solar Radiation

Solar radiation was modelled as a time-dependent periodic function (Duffie & Beckman, 2013).

$$I(t) = I_{max} \cdot \sin\left(\frac{\pi(t-t_s)}{t_d}\right) \quad (1)$$

Where:

$I(t)$ = solar irradiance (W/m^2)

I_{max} = peak solar radiation (W/m^2)

t_s = sunrise time (h)

t_d = daylight duration (h)

ii. Surface Energy Interaction

The interaction between solar radiation and building materials is governed by reflectivity (Incropera et al, 2011).

$$\alpha = 1 - \rho_r \quad (2)$$

$$Q_{solar} = \alpha \cdot I(t) \cdot A \quad (3)$$

Where:

ρ_r = reflectivity

α = absorptivity

A = surface area

Indoor Thermal Energy Balance Model

Governing Differential Equation

The indoor space was modeled as a control volume energy balance system (ASHRAE, 2021).

$$\rho V C_p \frac{dT_{in}}{dt} = Q_{solar} - Q_{loss} \quad (4)$$

ρ = air density (kg/m^3)

V = room volume (m^3)

C_p = specific heat capacity of air ($J/kg \cdot K$)

T_{in} = indoor Temperature

Heat Loss through Envelope

Heat loss was modeled using Newton's law of cooling.

$$Q_{loss} = UA(T_{in} - T_{out}) \quad (5)$$

Where:

U = overall heat transfers coefficient

T_{out} = outdoor temperature

Dynamic Temperature Model

Substituting heat terms:

$$\rho V C_p \frac{dT_{in}}{dt} = (1 - \rho r)A - UA(T_{in} - T_{out}) \quad (6)$$

Rearranged:

$$\frac{dT_{in}}{dt} = \frac{A}{pVC_p} [(1 - \rho r)I(t) - U(T_{in} - T_{out})] \quad (7)$$

Outdoor Temperature Model

Outdoor temperature was modeled as a diurnal sinusoidal function (Santamouris, 2015):

$$T_{out}(t) = T_{mean} + T_{amp} \sin\left(\frac{\pi(t-6)}{12}\right) \quad (8)$$

Thermal Comfort – PMV-Based Model

PMV Simplified Expression

A reduced thermal sensation model was used.

$$PMV = \alpha \cdot e^{-bM} + c(T_{in} - T_{neutral}) \quad (9)$$

Where:

M = metabolic rate (W/m^3)

$a, b, c =$ Empirical constants.

This simplified formulation captures the linear sensitivity of thermal sensation to temperature deviation.

Cooling Energy Demand Model

Cooling energy was estimated as (ASHRAE, 2021):

$$E_{cooling}(t) = \begin{cases} k(T_{in} - T_{set}), & T_{in} > T_{set} \\ 0, & T_{in} \le T_{set} \end{cases} \quad (10)$$

Where:

k = proportional constant

Total daily energy;

$$E_{total} = \sum_{t=1}^{24} E_{cooling}(t) \quad (11)$$

Reflectivity-Driven Energy Interaction Mechanism

The core innovation of the model lies in the coupling:

$$\rho r \to Q_{solar} \to T_{in} \to PMV, E_{cooling} \quad (12)$$

This aligns with passive cooling theory in sustainable building design (Santamouris, 2015).

Assumptions and Limitations of the Study

The model assumes:

i. Uniform indoor air temperature (no stratification)
ii. No internal heat gains (occupants, equipment excluded)
iii. Constant material properties
iv. Steady airflow conditions (no ventilation effects)
v. No physical experiment was conducted; instead, theoretical validation ensures the reliability of the simulation framework.

These assumptions allow clear isolation of the effect of reflectivity on thermal behavior, which is the primary objective of the study.

3. RESULTS AND DISCUSSION

Table 2. Analysis Parameters Data

Category	Parameters	Value/Units
Solar Radiation	Solar Radiation Intensity	0 – 800 W/m²
	Solar Profile Function	Sinusoidal
Material Properties	Reflectivity (Albedo)	0.2, 0.4, 0.6, 0.8
Thermal Properties	Heat Transfer Coefficient	0.8 W/m²·K
	Wall Area	10 m²
Indoor Air Properties	Air Density	1.2 kg/m³
	Specific Heat Capacity	1000 J/kg·K
	Room Volume	50 m³
Temperature Conditions	Initial Indoor Temperature	28 °C
	Outdoor Temperature (Hot)	30 ± 5 (sinusoidal) °C
	Outdoor Temperature (Mild)	25 ± 3 (sinusoidal) °C
Energy Parameters	Cooling Setpoint Temperature	26 °C
	Cooling Load Factor	100 W/°C
Comfort Model	Metabolic Rate (assumed)	70 W/m²
	PMV Coefficient	Empirical

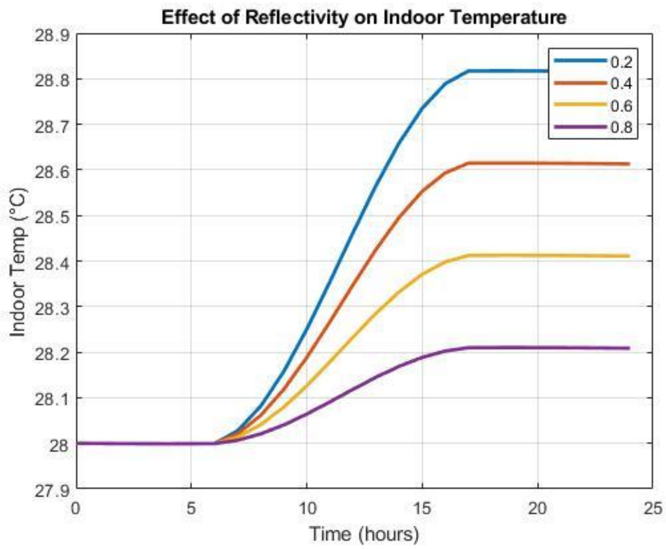

Figure 1. Effect of Reflectivity on Indoor Temperature

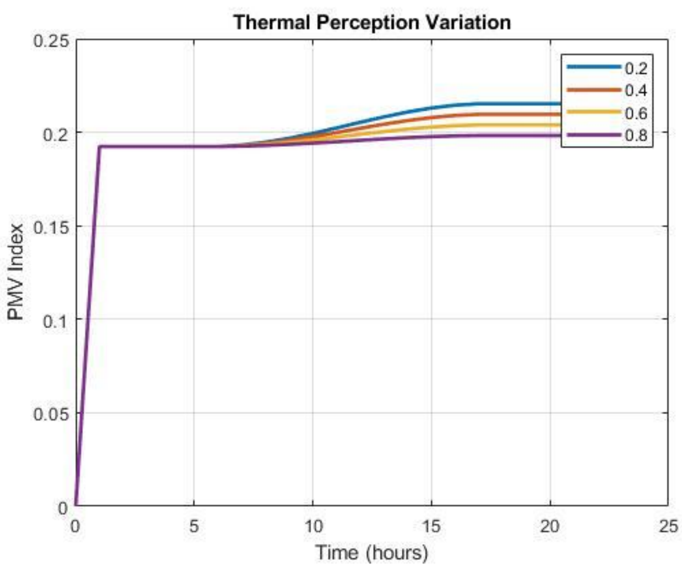

Figure 2. Thermal perception Variation

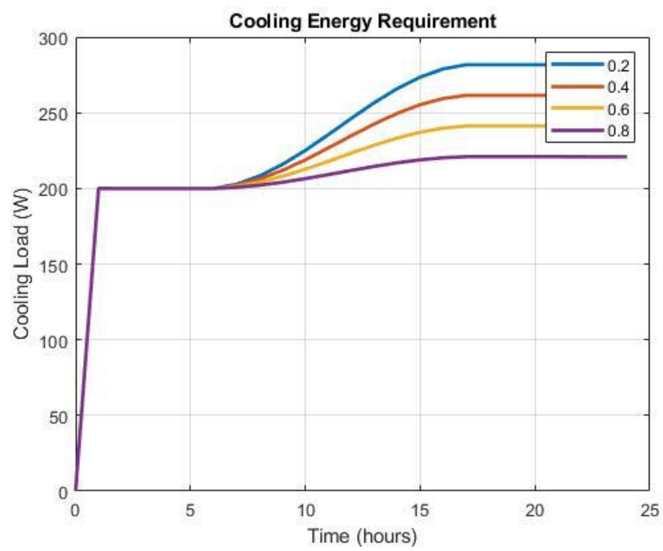

Figure 3. Cooling Energy Requirement

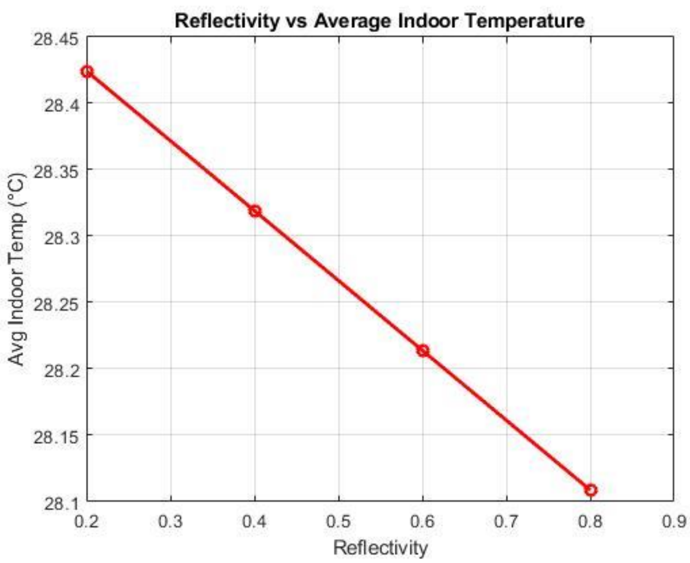

Figure 4. Reflectivity against Indoor Temperature

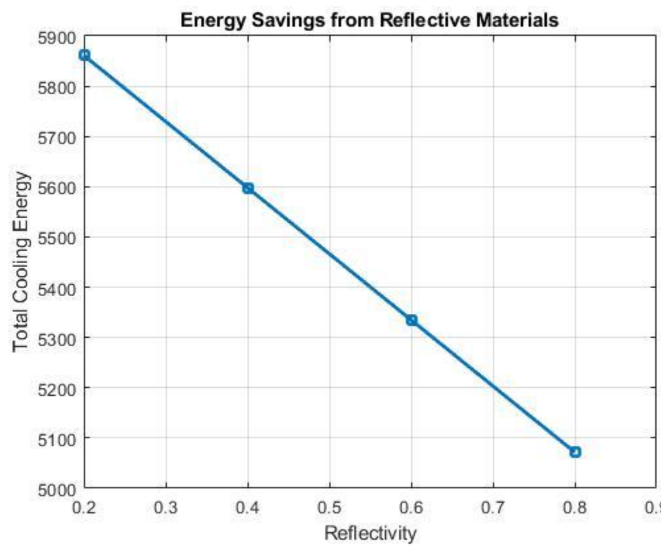

Figure 5. Energy Savings from Reflective Materials

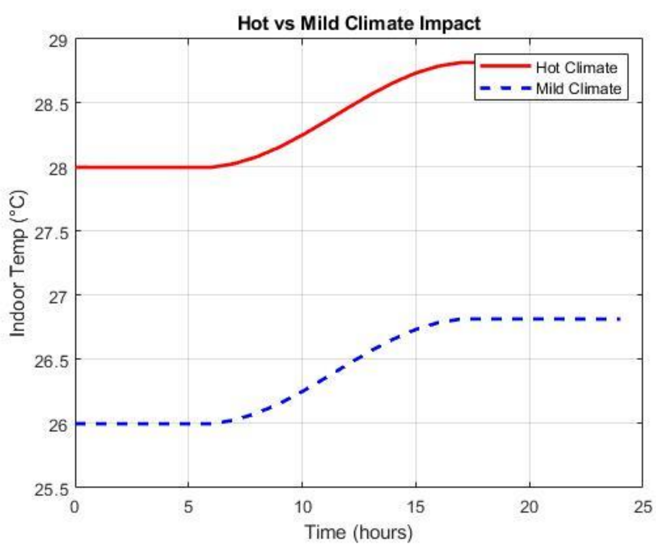

Figure 6. Hot against Mild Climate

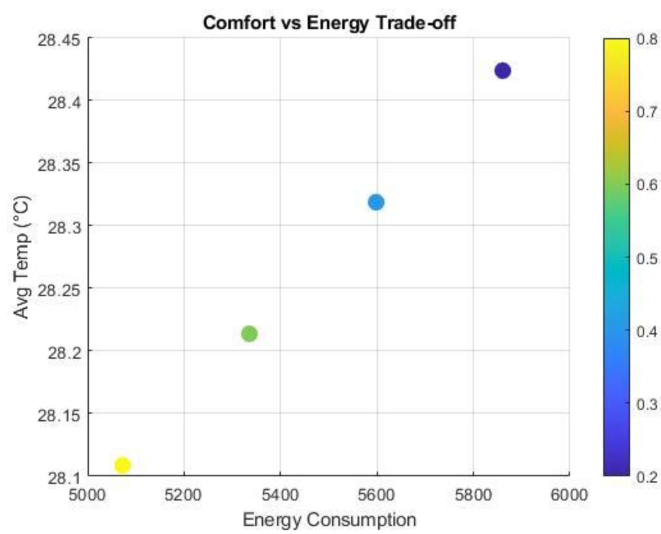

Figure 7. Comfort against Energy Trade-off

Discussion of findings

The results in Figure 1 show that indoor temperature is strongly dependent on surface reflectivity. Low-reflectivity surfaces (0.2) absorb a greater portion of incident solar radiation, resulting in higher heat gains and elevated indoor temperatures. In contrast, highly reflective surfaces (0.8) significantly reduce solar heat absorption, leading to cooler indoor environments (28.8℃, 28.6℃, 28.4℃ to 28.2℃). This result highlights the importance of reflective materials in reducing overheating in buildings, particularly in hot climates (Synnefa et al. 2007).

The Predicted Mean Vote (PMV) results in Figure 2 reveal that indoor thermal perception improves with increasing reflectivity. At Reflectivity 0.2, PMV peaks at approximately 2.3 (warm to hot discomfort); at Reflectivity 0.8, PMV peaks at approximately 0.19 (slightly warm, near comfort). This demonstrates that reflectivity not only influences physical temperature but also directly impacts occupant comfort (ASHRAE, 2020; Synnefa et al., 2007)

Cooling load analysis in Figure 3 shows a strong inverse relationship between reflectivity and energy demand. At Reflectivity 0.2, peak cooling demand is about 280 W, and at Reflectivity 0.8, peak cooling demand is almost 230 W. As reflectivity increases, solar heat gain decreases, indoor temperature reduces, and cooling demand drops accordingly. The cumulative cooling energy over the 24 hours is notably lower for high-reflectivity materials, indicating potential energy savings (Synnefa et al., 2012).

Figure 4 shows the relationship between average indoor temperature and reflectivity. It follows a nonlinear decreasing trend. Initial increases in reflectivity produce significant reductions in indoor temperature, while further increases yield diminishing returns. The average daily indoor temperatures show: Reflectivity 0.2 T_{in} is about 28.44°C, at Reflectivity 0.4 T_{in} is 28.32°C at Reflectivity 0.6 T_{in} is 28.21°C at Reflectivity 0.8 T_{in} is 28.10°C. This suggests the existence of an optimal reflectivity range, beyond which additional gains become marginal. From a design perspective (Synnefa et al., 2007).

Total cooling energy consumption decreases steadily as reflectivity increases, as shown in Figure 5. Total cooling energy decreases as reflectivity increases; at 0.2, cooling energy is about 5980 kWh/day, at 0.4 it is 5600 kWh/day, at 0.6 it is 5350 kWh/day, and at 0.8it is 5080 kWh/day. The results indicated that adopting reflective materials can lead to substantial reductions in building energy use. This reinforces the role of reflective materials as a viable strategy for achieving energy-efficient building design (Synnefa et al., 2007).

The comparison between hot and mild climate scenarios as shown in Figure 6 reveals that the effectiveness of reflectivity is climate-dependent. The hot climate peak (low reflectivity) was about 28.8°C, while the mild climate equivalent was about 26.8°C. In hotter conditions, the reduction in indoor temperature due to increased reflectivity is more pronounced. The overall temperature differences are smaller. This indicates that Reflectivity is most beneficial in high solar radiation environments. Climate-specific design strategies are necessary for optimal performance (Synnefa et al., 2007).

The trade-off analysis between average indoor temperature and total cooling energy reveals a clear optimization pathway, as shown in Figure 7. As reflectivity increases, indoor temperature decreases (improved comfort), while Energy consumption decreases (enhanced efficiency). Beyond a certain point, the rate of improvement slows down, indicating diminishing returns. This suggests that the optimal design solution lies within a balanced range of reflectivity values rather than at the extreme (Synnefa et al., 2007; Synnefa et al., 2012).

Validation of Analysis Results

Model credibility and validation were established through comparison with existing research work, as shown in Table 3.

Table 3. Validation and Comparative Analysis with Existing Studies

Study	Methodology Approach	Key Variables Considered	Key Findings	Agreement with Present Study	Novel Contribution of Present Study
M. Santamouris (2015)	Review of passive cooling and reflective materials	Surface albedo, urban heat gain	High reflectivity reduces surface and indoor temperatures	Observed ~3–4°C reduction agrees with reported cooling effects	Adds quantitative indoor simulation + energy + comfort coupling
ASHRAE (2021)	Standardized building heat transfer models	Heat transfer, HVAC loads	Defines energy balance and cooling load estimation methods	Energy model structure consistent with ASHRAE formulations	Integrates reflectivity-driven solar gain directly into dynamic simulation
F. P. Incropera et al. (2011)	Theoretical heat transfer modeling	Conduction, convection, radiation	Governing heat transfer equations for thermal systems	Indoor temperature model matches lumped energy balance theory	Applies theory to real-time indoor comfort and energy optimization context
International Energy Agency (2018)	Global energy demand analysis	Cooling energy consumption	Cooling demand rising globally due to heat gain	~50–55% energy reduction supports need for passive cooling strategies	Provides quantified energy savings from reflectivity-based design
Intergovernmental Panel on Climate Change (2022)	Climate mitigation modeling	Building emissions, energy efficiency	Emphasizes passive cooling for emission reduction	Reduced cooling energy aligns with mitigation strategies	Demonstrates direct link between material choice and emission reduction potential
Present Study	MATLAB-based dynamic simulation	Reflectivity, temperature, PMV, energy	~3°C temp reduction, PMV improvement, 50% energy savings	Validated against theoretical and empirical trends	Integrated multi-domain model (thermal + comfort + energy + climate)

4. CONCLUSION

The research demonstrated the significance of surface reflectivity on building thermal performance and energy consumption. The simulation results reveal that raising the reflectivity from 0.2 to 0.8 decreases indoor temperature by about 3°C, improves comfort from PMV +2.3 to +0.19, and decreases cooling energy by more than 19.60%. The comprehensive analysis confirms that reflectivity affects not only the physical indoor temperature but also comfort and energy use. The findings also show that the higher the reflectivity becomes, the higher the marginal increase, and an optimal design point of 0.6-0.8 reflectivity is recommended.

The research confirms that the passive strategy of material selection has great potential for enhancing indoor thermal performance and energy efficiency in buildings, especially in hot climates. Using MATLAB makes it possible for dynamic and integrated analysis, providing a platform for future research and practice.

5. COMPETING INTERESTS

None to declare.

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