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Article

Theoretical Analysis of Trombe Wall Performance: Evaluating Key Parameters for System Efficiency

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Abstract

With rising energy consumption and greenhouse gas emissions particularly carbon dioxide (CO_2) optimizing fossil fuel use and improving passive heating/cooling systems in buildings has become crucial. Trombe walls, as a sustainable solar heating solution, can significantly reduce energy demand by storing and releasing heat effectively. This study investigates the influence of thermal storage wall materials on the performance of Trombe wall systems through numerical analysis. Different multi-layer wall configurations incorporating brick, adobe, stone, and plaster-concrete-insulation composites were evaluated under varying solar radiation conditions (100-620 W/m²) over an 8-hour period (9 AM-5 PM). Results demonstrate that brick-based walls achieved superior room temperature regulation (21.25 °C vs. 20.53 °C for adobe at 620 W/m²), with thermal resistance proving more critical than material thickness. Comparative analysis revealed that plaster-concrete-insulation walls outperformed traditional materials in heating efficiency. Additionally, the study examined modified heat transfer equations for air ducts, finding that existing theoretical models (15.12 °C prediction at 11 AM) aligned more closely with experimental data (17.5 °C) than the proposed modifications (14.06 °C). The study provides clear design principles for Trombe wall optimization: prioritizing thermal-resistant materials (e.g., brick, insulated composites) over thickness and using validated heat transfer models. These insights enable more effective passive heating systems that lower energy demands in buildings. By implementing these strategies, construction professionals can significantly improve thermal performance while contributing to climate change mitigation through reduced carbon footprints.

Keywords

Trombe wall, TWsim software, Solar energy, Thermal storage wall, Sustainable architecture

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1. Introduction

The increasing global energy demand coupled with environmental concerns has intensified the need for sustainable building solutions. Among various passive solar technologies, Trombe walls have emerged as an effective method for space heating that significantly reduces energy consumption in buildings. This passive system operates through a simple yet efficient mechanism that captures, stores, and gradually releases solar energy. The fundamental Trombe wall design consists of three key components: a thermal storage wall, an air cavity, and a glazing layer. Solar radiation passes through the glazing and is absorbed by the thermal mass wall. The stored heat then transfers to indoor spaces through conduction and natural convection, maintaining comfortable temperatures with minimal energy input. This process makes Trombe walls particularly valuable for reducing heating demands in cold climates while maintaining indoor thermal comfort. Recent advancements in Trombe wall technology have focused on optimizing performance through material innovation and system configurations. The integration of these improvements has led to more versatile systems capable of providing year-round benefits. As buildings account for a substantial portion of global energy use, technologies like Trombe walls represent important solutions for sustainable development. Their ability to provide clean, renewable heating aligns with global efforts to reduce carbon emissions from the built environment. When properly designed and implemented, these systems can significantly lower operational energy demands while maintaining occupant comfort [1-3]. Among the effective and important factors in this heating system, we can mention the insulation [4-5], vent [6-7] and the thickness of the thermal wall [8-9]. Proper insulation prevents heat loss during nighttime operation while maintaining optimal thermal storage capacity. Vent design directly controls airflow patterns, with optimal sizing and positioning ensuring efficient heat distribution into living spaces while preventing overheating. The thermal wall thickness affects both heat storage capacity and time lag characteristics, with thicker walls providing greater thermal mass but requiring longer heat release periods. Advanced materials are showing particular promise in further enhancing Trombe wall performance across different climatic conditions. Future research should focus on developing adaptive control systems that dynamically adjust these parameters in response to real-time thermal demand and weather variations.

Many studies have been conducted in the last few decades to boost the effectiveness of the Trombe wall. Abdelsamea et al. [10] developed an enhanced multi-story Trombe wall system that integrates passive heating, cooling, and photovoltaic functions. The optimized design demonstrated improved performance, reducing cooling loads by 1.94 °C, increasing heating capacity by 1.56 °C, boosting thermal comfort hours by 40%, and raising annual PV electricity generation by 31% compared to conventional systems. Elsaid et al. [11] investigated Trombe wall optimization for winter heating in Egypt's arid climate, testing different air gap widths (100-300 mm) and ventilation modes. Their results showed optimal performance with a 300 mm air gap using top-door ventilation (Mode-II) and gate pattern-A, aligning with previous winter-condition studies. Bulmez et al. [12] developed an innovative dual-layer Trombe wall system with forced convection that enhanced indoor ventilation year-round, achieving temperature increases of 3.4-15.99 °C in Brașov (cold climate) and 6.42-12.07 °C in Constanța (hot climate), with solar radiation contributing an average 2 °C gain across Romania's seasonal variations.

Bevilacqua et al. [13] validated a Thermo-Diode Trombe Wall model showing optimal performance with 24 cm solar cavity thickness, achieving >35 °C air temperatures while maintaining <0.2 m/s airflow and 28 W/m² peak heat transfer, effectively balancing solar gain with insulation requirements for modern energy regulations. Zhang et al. [14] developed a novel PCM-enhanced Trombe wall that delays peak temperature by 4 hours, reduces indoor temperature fluctuations by 68.4%, maintains stable 18.2 °C indoor temperatures, and improves thermal comfort through optimized air velocity control compared to conventional systems. Mustafa et al .[15] demonstrated that semicircular (SEC) phase-change material obstacles in solar walls outperform rectangular ones (REC), increasing Trombe wall temperature by 2.1 °C and outlet air temperature above 295.5 K while extending PCM freezing time by 15 minutes during 7-hour radiation-free periods. Romdhane et al. [16] demonstrated through computational fluid dynamics (CFD) simulations that Trombe walls in Lille's climate maintain higher upper vent temperatures (creating natural airflow) and perform optimally with medium wall thickness and narrow air gaps, providing valuable design insights for efficient passive heating systems.

The Trombe wall is an innovative passive solar heating system that combines glass panels with thermal mass materials (such as masonry, stone, or concrete) to absorb and store solar energy for space heating. When sunlight passes through the glass, it heats the wall surface, which then radiates warmth into the building. The air gap between the glass and the wall creates a convection cycle, hot air rises and enters the room through upper vents, while cooler air returns through lower vents, ensuring continuous heat distribution. Additionally, the thermal mass retains heat, providing consistent warmth even after sunset [17-19]. The software of TWsim is considered as a simulator of the Trombe wall by Hashemi et al. [20] and is used to optimize the parameters of this system. This software has three parts: result, data process and basic data. By engaging in the data processing of the Trombe wall system, significant modifications can be achieved. To initiate the software, users need to input essential process details, encompassing dimensions of the wall and glass, heat transfer coefficients of the wall and glass, distance between them, and more. Subsequently, the software computes temperature variations, encompassing alterations in room temperature, predicated on the system's utilization. This software displays outcomes like room temperature variations.

This study evaluates the performance of different thermal storage wall materials to improve the efficiency of Trombe wall systems based on room temperature variations, which has received less attention in previous studies. Additionally, the effect of heat transfer coefficients on room temperature is thoroughly examined through thermal equation analysis, and a modified equation is proposed to assess room conditions for evaluation in Trombe wall software. This approach could enhance the Trombe wall software by transforming a single-equation heat transfer coefficient into a multi-option feature for users, adding significant value to the software's computational capabilities. In this study, we carefully analyze the Trombe wall simulation software (TWsim), examining both its strengths and weaknesses. We also explore ways to improve future versions of the program, providing important recommendations for its development.

2. Methodology

2.1 TWsim Software

TWsim represents a significant advancement in passive solar design technology, providing engineers and architects with a comprehensive simulation tool specifically developed for Trombe wall systems [20]. This specialized software addresses the complex thermal dynamics of Trombe walls through an intuitive interface that combines scientific rigor with practical usability. The software's architecture follows a logical three-part structure that guides users through the design process. The input section collects all necessary parameters, organized into basic material properties and process-specific variables. This division allows for both quick standard configurations and detailed custom designs. Users can select from common building materials while adjusting critical dimensions like wall thickness and air gap sizes, with the software automatically accounting for each material's thermal characteristics.

At its computational core, TWsim employs validated heat transfer equations that model all three modes of heat transfer: radiation through the glazing, conduction within the massive wall, and convection in the air channel. The program calculates temperature distributions across system components while simulating the natural airflow patterns that are fundamental to Trombe wall operation. These calculations consider temporal variations, allowing analysis of daily performance cycles under specified solar radiation conditions. What sets TWsim apart is its sophisticated yet accessible results interface. The software generates clear visualizations of temperature gradients along the wall height, showing how heat accumulates and transfers through the system. Comparative analyses become straightforward, enabling users to evaluate multiple design variants efficiently. The graphical output reveals subtle performance characteristics that might be missed in manual calculations, such as the nonlinear temperature profiles in the air channel or the time lag effects in thermal storage walls. The practical applications of TWsim extend across the building design process. During preliminary design, architects can quickly assess feasibility and approximate dimensions. Engineers benefit from precise performance predictions when finalizing specifications. The software also serves as an educational tool, helping students visualize the thermodynamic principles underlying passive solar systems through interactive experimentation.

Current capabilities include simulation of winter heating performance with various common wall materials under user-defined climatic conditions. The software's modular structure suggests potential for future expansions, such as summer cooling analyses or integration with broader building energy modeling platforms. This adaptability positions TWsim as a growing resource in sustainable design toolkits. By bridging the gap between theoretical models and real-world applications, TWsim enables more confident adoption of Trombe wall technology. Its balanced approach to accuracy and usability makes sophisticated passive solar design accessible to professionals across experience levels, contributing to wider implementation of this energy-efficient building solution.

2.1.1 Strengths and Weaknesses of TWsim Software

The TWsim program has numerous strengths that make it a perfect program for studying wall heat transfer. One of the program's best features is its simplicity. The program is minimal and well-organized, and the input and results areas are defined clearly. This makes the program accessible to both experts and beginners with limited experience.

Another of its important strengths is in the precision of calculations. TWsim is based on proven scientific formulas for simulating real heat transfer behavior. In most cases, results calculated using the software are well correlated with experiment results, giving high confidence in its accuracy. Add to this the software also offers utilitarian capabilities. Users can test different wall materials, change design parameters such as wall thickness and air space, and even apply actual weather conditions to evaluate performance in real-world conditions.

In addition to accuracy and flexibility, TWsim provides helpful visual outputs. The program generates simple graphs to show how temperatures change over time and how different designs of walls compare. The graphs reduce complex data to simple comparisons and allow people to make easier choices. Another benefit is that the program conserves time by avoiding complex calculations. It can quickly test many design options, which avoids costly mistakes during the planning stage.

Despite these advantages, TWsim also has several weaknesses. One limitation is the small choice of wall materials. The program includes only the default options and does not cover newer or unusual materials, such as phase-change or composite materials. This reduces its applicability to projects involving advanced designs. Weather treatment is also an area where the program is less advanced. It employs simple solar radiation inputs and doesn't automatically model seasonal variations, which lowers its applicability to different climates.

TWsim also focuses mainly on heating performance. It is unable to analyze cooling or summer overheating and therefore cannot present a correct year-round thermal performance image. Furthermore, the software utilizes base coefficients fixed heat transfer values. These values may not encompass special conditions, and the results therefore may not always represent actual conditions. Finally, TWsim is a stand-alone system. It is not easy to integrate it with other design or simulation packages, and it only has restricted options of exporting data. This also makes it more challenging to integrate into whole building design projects where multiple tools are usually used simultaneously.

In brief, TWsim is a realistic and reliable heat transfer research tool for walls, with the benefits of usability, accuracy, and visualization. Its limitations are few materials, basic weather treatment, absence of cooling analysis, fixed heat transfer values, and being stand-alone restrict its use to more complex or modern building plans.

2.1.2 Equations in TWsim Software

For thermal storage walls with ventilation features, the governing equation is provided by [17]:

$$a_s \cdot Q_{solar} . t_g = \varepsilon_{w\text{-}g}\ \sigma \left[\left(\frac{T_{w(x)}+273}{100}\right)^4 - \left(\frac{T_{g(x)}+273}{100}\right)^4\right] + h_{cw}\left(T_{w(x)}-T_{aw(x)}\right) + h_{i_w}\left(T_{w(x)}-T_{room}\right) \quad (1)$$

The software also calculates glass temperature changes based on its thermal properties [17]:

$$\varepsilon_{w\text{-}g}\ \sigma \left[\left(\frac{T_{w(x)}+273}{100}\right)^4 - \left(\frac{T_{g(x)}+273}{100}\right)^4\right] \pm \quad h_{cg}\left(T_{g(x)}-T_{ag(x)}\right) = \varepsilon_2\ \sigma \left[\left(\frac{T_{g(x)}+273}{100}\right)^4 - \left(\frac{T_s+273}{100}\right)^4\right] + h_o\left(T_{g(x)}-T_o\right) \quad (2)$$

For analyzing room temperature variations, the methodologies presented in references [18,20] are employed.

$$T_{room} - T^{i}_{room} = \frac{Q}{C_p\ \rho\ V_{room}}\ t \quad (3)$$

$$Q = m.cp.(Tm-Tin) \quad (4)$$

In the above equation, m represents the air mass volume and T_m denotes the average temperature in the channel.

This study conducts a comprehensive thermal analysis of various wall materials to evaluate their potential integration into future versions of the Trombe wall simulation software. The research focuses on characterizing traditional options like brick and clay [21-22], along with advanced Phase Change Materials (PCMs) [23-24], to assess their suitability for digital modeling.

For conventional materials, the investigation examines thermal storage capacity, conductivity profiles, and optimal thickness ranges under different solar radiation conditions.

2.2 The Development of TWsim Software Based on Modified Equations

In this study, unlike the previous study [18], the heat transfer coefficient of the channel air can be defined as follows (based on the system including a wall and a glass) [25]:

$$hc = \frac{k.\,Nu}{b} \quad (5)$$

In equation 11, Nu, k and b are Nusselt number, thermal conductivity and channel width, respectively. For the Nusselt number, we can write [25]:

$$Nu = \mathrm{Nu} = 0.68 + \frac{0.67(Re)^{1/4}}{[\ 1+(0.492/Pr)^{\frac{9}{16}}]^{4/9}} \quad (6)$$

In the above relation, Re represent Reynolds number. It should be noted that to calculate the Reynolds number, the channel air velocity equation is studied as follows in this study [26]:

$$v_a = \left[\frac{2\ \Delta p}{\rho\ \left(c_1 \left(\frac{A_c}{A_i}\right)^2 + c_2 \frac{z}{w} + c_3 \left(\frac{A_c}{A_o}\right)^2\right)}\right] \quad (7)$$

2.3 Calculation Process

Based on the equations defined in this study, the program follows the following step-by-step calculation procedure:

2.3.1 Step 1: Input initial Parameters

The process initiates by entering all input data needed:

Solar radiation intensity.

Wall and glass thermal properties (emissivity ε, Stefan-Boltzmann constant σ).

Physical dimensions of air channel.

Initial temperature values for room.

2.3.2 Step 2: Wall Temperature Calculation

Using Equation (1), the program calculates:

Radiative heat transfer between the glass surfaces and the wall.

Convective heat transfer at the wall-air interface.

Internal heat transfer from the wall to the room.

The outcome is a new wall temperature profile.

2.3.3 Step 3: Compute the Glass Temperature

Equation (2) is solved to obtain:

Radiative balance between the wall and the glass.

Convective heat transfer in the air channel.

Externally incurred heat losses through glass.

This provides the new glass temperature.

2.3.4 Step 4: Update Room Temperature

The final thermal calculations:

Compute heat contribution (Q) from channel air using Equation (4).

Update room temperature (Troom) using Equation (3) based on: air mass flow rate (m), specific heat capacity (cp), room volume (Vroom).

2.3.5 Step 5: Iterative Solution

The program repeats Steps 2-4 until: temperature changes between iterations are less than a specified tolerance, energy balance conditions are met, stable solutions are derived for all the components.

3. Results and Discussion

3.1 Room Temperature Changes Based on Number of Wall Layers

In this research, the significance of the thermal storage wall material in the Trombe wall system is addressed. The study explores the performance of a multi-layer wall incorporating materials like stone, brick, and concrete, alongside glass. The findings are summarized in Table 1.

Table 1. Multi-layer wall performance in room temperature changes based on Trombe wall system.

Wall Components	Room Temperature Changes (°c)							
	1 h	2 h	3 h	4 h	5 h	6 h	7 h	8 h
Stone (0.3 m)	14.62	15.90	17.2	18.58	19.95	21.26	22.07	22.1
Adobe (0.2 m)	14.73	16.15	17.56	19.05	20.53	21.94	22.83	22.9
Brick (0.2 m)	14.82	16.39	18.09	19.68	21.25	22.75	23.68	23.8
Concrete (0.24 m) + Insulation (0.02 m) +Plaster (0.015 m)	14.94	16.62	18.46	20.16	21.83	23.42	24.38	24.48

To calculate the temperature changes created in the room based on different materials, the details of reference [18,21] have been taken into account and information such as the geometric dimensions of the room, temperature and amount of radiation (during the time period from 9 am to 5 pm) has been used.According to Table 1, room temperature changes based on different layers in the heat storage wall have been numerically studied for 8 hours during the day. Solar radiation was 460 w/m^2 at 9 am and 100 w/m^2 at 5 pm. The table results highlight the crucial role of thermal storage wall components in this system, with variations based on material thickness and thermal conductivity parameters. Based on the results of Table 1, for the three materials of brick, Adobe and stone, the more favorable room temperature changes are in the brick-based wall. The study results indicate that Plaster + Concrete + Insulation, outperform walls based on stone, clay, and brick in terms of room heating efficiency.

The results of this study clearly demonstrate that the thermal resistance characteristics of wall materials have a more significant impact on system performance than wall thickness alone. As shown in Table 1, under identical solar radiation conditions of 620 W/m², the brick-walled system maintained a room temperature of 21.25 °C, while the adobe-walled system achieved only 20.53 °C - a measurable 0.72 °C difference despite both walls having equal thickness. This finding provides important insights into heat transfer mechanisms in passive solar systems. The superior performance of brick can be attributed to its optimal combination of thermal conductivity and volumetric heat capacity, which creates more efficient heat transfer pathways compared to adobe. These material properties enable brick to more effectively absorb solar radiation during peak hours while maintaining better temperature regulation through controlled heat release.

These findings have important practical implications for Trombe wall design. Rather than simply increasing wall thickness, designers should focus on selecting materials with appropriate thermal resistance properties that match specific climatic conditions and performance requirements. Brick's demonstrated advantages in this study suggest it may be particularly suitable for applications requiring efficient heat storage and gradual release. However, the research also highlights the need for comprehensive material evaluation, as other factors like cost, availability, and structural requirements must also be considered in real-world applications.

3.2 Effect of Channel Air Heat Transfer Coefficient Based on Room Temperature Changes

In Figure 1, the changes in the room temperature is presented based on the modified equations based on the air heat transfer coefficient of the duct. As can be seen in Figure 1, the process of predicting room temperature changes based on the equations modified in this study compared to the previous theoretical study had more differences with the experimental results, and it seems that the previous equations have a better performance for predicting room temperature changes. In such a way that at 11 o'clock based on the solar radiation of 560 w/m^2 and the outside temperature of 4 ^{o}C, the prediction of the room temperature based on the equations of the previous study and this study, respectively 15.12 and 14.06 ^{o}C (experimental result: 17.5 ^{o}C). Also, at 15:00 p.m., based on the solar radiation of 590 w/m^2 and the outside temperature of 15 ^{o}C, the experimental result of the room temperature is 20.6 ^{o}C, and the prediction of the room temperature based on the equations of the previous study and this study, respectively, is 19. 7 and 15.01 ^{o}C.

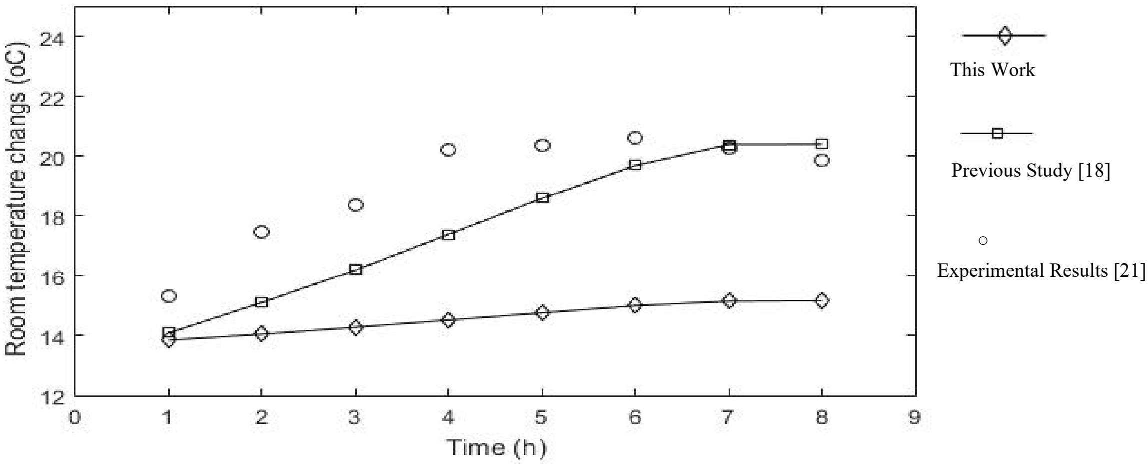

Figure 1. Room temperature changes due to effect of channel air heat transfer coefficient.

3.3 Suggested Improvements in TWsim Software for Advanced Trombe Wall Optimization

TWsim is a major step forward in passive solar design software that offers architects and engineers a specialist tool for the simulation of Trombe walls. As can be observed from this work, the program effectively simulates the principal thermal processes of radiation absorption, heat storage, and natural convection. With its existing capabilities, users can try different wall materials, vary key dimensions, and predict system performance under varying solar loads. However, a few promising directions for development can carry TWsim from a useful design assistant to an invaluable all-encompassing tool for sustainable building optimization. A few future releases should include:

(1) Material science integration: expand the material palette beyond conventional ones (brick, concrete), employ phase-change materials (PCMs) with temperature dependent properties, add hybrid material pairs and nanocomposites, combine clean insulation products for enhanced glazing solutions.

(2) Advanced climate adaptation: incorporate location-specific climatic patterns, incorporate seasonally perform analysis functionality, incorporate microclimate factors (urban heat island impacts), develop region-specific design recommendation algorithms

(3) System configuration flexibility: accommodate photovoltaic-Trombe wall hybrid simulation, incorporate ventilated Trombe wall summer options, incorporate automated vent control simulations, accommodate curved or angled wall configurations.

(4) Machine learning enhancement: develop predictive models for unconventional designs, implement performance optimization algorithms, create smart design recommendation systems, enable pattern recognition from existing successful installations

3.3.1 Machine Learning Integration Potential

The combination of traditional thermal modeling with machine learning (ML) techniques presents particularly exciting opportunities for TWsim's evolution. ML could enhance the software in several key ways:

(1) Performance prediction: train models on extensive simulation and experimental data, predict outcomes for untested configurations, reduce computation time for complex scenarios.

(2) Design optimization: implement genetic algorithms to find optimal configurations, develop neural networks that suggest improvements, create adaptive systems that learn from user preferences.

(3) Fault detection: identify potential design flaws automatically, suggest corrective measures for suboptimal designs, learn from common mistakes in Trombe wall implementation.

(4) Climate-specific solutions: analyze vast climate datasets to find optimal designs, adapt models to local weather patterns, predict long-term performance under climate change scenarios.

While TWsim currently provides valuable Trombe wall simulation capabilities, its possibilities are far more extensive than current capabilities. Incorporating advanced material simulation, climate adaptation modes, and machine learning capability, the software could become the industry standard for passive solar design. Merging thermal physics with data-driven approaches would be particularly disruptive to how we design and calibrate building energy systems. This advancement would put TWsim on the leading edge of green design technology, bridging the divide between traditional architectural practice and Complex computational methods. As the building industry moves toward net-zero, these advanced tools would increasingly be essential in building high-performance, energy-efficient structures. The direction of development outlined here would maintain TWsim as a valuable and useful tool in this rapidly changing.

4. Conclusion

The urgent global challenge of reducing carbon emissions in the built environment demands innovative solutions that prioritize renewable energy integration and passive design strategies. Buildings account for nearly 40% of global energy consumption and associated emissions, making sustainable heating solutions like Trombe walls essential for achieving climate targets. This study highlights how passive solar systems can significantly contribute to energy management by harnessing freely available solar radiation while minimizing reliance on fossil fuel-based heating. The demonstrated performance advantages of brick walls over stone alternatives reinforce the importance of material science in developing effective carbon-neutral heating solutions. Our findings provide crucial evidence supporting the wider adoption of Trombe walls as part of integrated energy management systems, particularly when combined with proper insulation and optimized air channel designs. The research underscores three key pillars for sustainable building practices: (1) strategic material selection to maximize thermal performance, (2) precision engineering of passive solar components, and (3) holistic system integration that considers both heating efficiency and embodied carbon impacts. These insights advance our understanding of how passive solar architecture can simultaneously address energy poverty and climate mitigation needs, particularly in sun-rich regions where solar potential remains underutilized. Future developments should focus on hybrid systems that combine Trombe walls with photovoltaic elements and smart controls, creating synergistic solutions for net-zero energy buildings. By demonstrating the quantifiable benefits of optimized Trombe wall configurations, this work provides a scientific foundation for policymakers and architects to accelerate the transition toward solar-optimized, low-carbon building stocks worldwide. This study thoroughly examined the strengths and limitations of the Trombe wall simulation software, identifying key areas for improvement to enhance its predictive accuracy and practical utility. The analysis revealed that while the software effectively models basic thermal performance, its current version would benefit from expanded material libraries, dynamic climate adaptation features, and advanced airflow modeling capabilities. We proposed specific upgrades including the integration of phase-change materials, seasonal performance analysis tools, and machine learning optimization modules. These recommended enhancements would transform the software into a more comprehensive design tool, enabling architects to create higher-performing Trombe wall systems. The findings provide a clear roadmap for developing next-generation simulation tools that better support low-carbon building design while maintaining user accessibility. Implementing these improvements will help bridge the gap between theoretical models and real-world installation requirements.

5. Future Research Directions and Challenges

The results obtained in Table 1 highlight the significant role of thermal storage wall materials in improving the efficiency of the Trombe wall system. These findings emphasize the importance of material selection in the design of such systems in buildings. Therefore, studying the use of different materials in this system remains crucial for enhancing its performance. One promising approach to developing the Trombe wall system based on material selection is the use of mineral stones. These stones can effectively absorb solar radiation due to their variety of colors and can be easily incorporated into buildings. Additionally, these mineral stones can be ground into powder and applied as slurry-based coatings on wall surfaces. Figure 2 shows some proposed mineral stone and powder samples for this purpose. Future studies will comprehensively analyze and evaluate these materials to expand and refine the current research. If favorable results are achieved, they will be considered for updates to the relevant software.

Figure 2. (a) Mineral stones suitable for use as thermal storage walls. (b) Mineral powders suitable for use as surface coatings in Trombe wall systems.

While mineral stones offer fascinating thermal properties for applications like Trombe walls, several practical issues must be addressed to install on a mass scale:

(1) Logistical challenges.

Transportation and accessibility: transportation of these materials to target areas (e.g., off-site or city buildings) can be costly and difficult due to their heaviness and volume.

Supply chain vulnerabilities: limited geographic proximity of the correct mineral stones can lead to dependence on scarce suppliers.

(2) Economic feasibility.

Price volatility: volatility of raw material prices could make project economics unstable, especially in price-sensitive markets.

Scalability: material or processing costs at an elevated cost level could deter large-scale adoption versus conventional alternatives.

(3) Technical considerations.

Durability and maintenance: long-term performance under changing climatic conditions (e.g., freeze-thaw, humidity) needs further substantiation.

Standardization: lack of uniform quality standards for mineral stones may affect consistency in thermal performance.

To reduce the risk associated with the nature of mineral stones (e.g., cost of transportation, price volatility, and supply uncertainty), the following risk management practices are recommended:

(1) Lightweight and composite material development.

Invest in composites made of engineered mineral stone or hybrid material technology to achieve weight reduction with minimal sacrifice in thermal efficiency.

This will lower transportation and handling costs, which will make large projects more feasible.

(2) Local sourcing and decentralized supply chains.

Procure mineral stone deposits locally in order to lower reliance on distant suppliers.

Establish regional processing facilities to reduce logistics expenses and lead times.

(3) Stabilization of costs and financial subsidy.

Facilitate government subsidy or tax breaks to offset price volatility of materials.

Facilitate bulk purchase agreements or long-term supply agreements to secure a stable price.

Facilitate public-private partnership in funding infrastructure for mineral stones' extractions and processing.

(4) Standardization and quality assurance.

Create industry standards for performance and mineral stone quality to promote consistency.

Create certification programs to give architects and builders assurance of material dependability.

By taking these steps, the building construction industry is able to reduce risks and enhance the performance of mineral stones in green building constructions.

Conflict of Interest

The authors declare that they have no conflict of interest.

Generative AI Statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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