Impact of Shading and Glazing Types of Trombe Walls on the Carbon Footprint of Residential Buildings in Morocco

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Abstract. This paper investigates the impact of shading and glazing types on the performance of Trombe walls in reducing the carbon footprint of Moroccan residential buildings. Trombe walls, as passive solar heating systems, offer significant potential for energy savings and carbon emissions reduction in residential constructions. Our study evaluates various shading devices and glazing materials to determine their effectiveness in optimizing thermal performance and minimizing energy consumption. Through simulation, we analyze the influence of different configurations on indoor temperature regulation and overall energy efficiency. The findings highlight that Triple Clear (TG 3-13) glazing achieves a substantial 22.5% annual decrease in CO_2 emissions compared to buildings without Trombe walls, while local shading for this glazing type increases emissions by 4.5%. Additionally, dynamic window shading controlled by a predefined schedule reduces emissions by 2% annually compared to static glazing setups. These results underscore the critical role of glazing selection and shading strategies in enhancing sustainability and reducing carbon footprints in Moroccan residential buildings. This research contributes to the development of energy-efficient building practices, supporting Morocco's commitment to reducing its carbon footprint and promoting environmental sustainability.

1 Introduction

1.1 Rationale and goals

The increasing urgency to address climate change has led to a growing emphasis on sustainable building practices worldwide [1]. In Morocco, residential buildings contribute significantly to the nation's energy consumption and carbon emissions, highlighting the need for innovative solutions to enhance energy efficiency [2]. One promising approach is the incorporation of Trombe walls, a passive solar heating system that leverages solar energy to regulate indoor temperatures [3].

Trombe walls consist of a thick wall painted black and covered with glass on the exterior, with a small air gap between the wall and the glazing. This setup absorbs solar radiation during the day, storing heat in the wall's mass and gradually releasing it into the building's interior at night [4]. While the basic concept of Trombe walls is well-established, the effectiveness of these systems can be significantly influenced by the types of shading and glazing used.

Shading devices play a crucial role in controlling the amount of solar radiation that reaches the Trombe wall, preventing overheating during the summer months while maximizing heat gain in the winter [5]. Similarly, the choice of glazing material affects the wall's thermal performance by influencing factors such as heat retention, light transmission, and insulation properties [6].

This paper aims to investigate the impact of different shading and glazing configurations on the performance of Trombe walls in Moroccan residential buildings. By evaluating various combinations through simulation, we seek to identify the most effective strategies for optimizing energy efficiency and reducing the carbon footprint. Our research provides practical insights for architects, builders, and policymakers striving to implement sustainable building practices in Morocco, thereby contributing to the nation's environmental goals and enhancing the comfort and well-being of its residents.

1.2 Literature review

Trombe walls, a passive solar design feature, play a significant role in regulating indoor temperatures by absorbing and slowly releasing solar energy. Their impact on the carbon footprint of residential buildings is particularly relevant in regions like Morocco, where solar irradiance is high. This review examines the effects of shading and glazing types on the efficiency of Trombe walls and their contribution to reducing the carbon footprint.

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Shading devices, such as overhangs, louvers, and vegetation, influence the performance of Trombe walls by controlling the amount of solar radiation that reaches the wall surface. Studies have shown that appropriately designed shading can significantly reduce cooling loads during the summer while allowing maximum solar gain in winter. For instance, research by Chen et al. [7] analyzed experimental data to investigate the heat preservation effect of a shading device on winter nights. They discussed the optimal fixed location of the shading in the air gap for minimizing heat loss and examined its influence on indoor thermal comfort using the building envelope response factor (BER) developed by Lukic. Similarly, a study by Ana Briga Sá et al. [5] found that when the ventilation system was turned off and the shading device was inactive, the temperature inside the test cell exceeded the outside temperature by 9°C, demonstrating the system's ability to store and release heat.

The type of glazing used in Trombe walls is crucial in determining their thermal performance. Single, double, and triple glazing each have distinct properties that affect heat transfer. Double and triple glazing, while more expensive, provide better insulation and reduce heat loss compared to single glazing. Research by Pourghorban A, et al. [6] found that using Trombe walls with advanced glazing units reduces the heating period by 48.8% and improves comfort conditions by 23.9%. However, it also increases the cooling period by 22.7% and overheating by 2.2%. Reducing window-to-wall ratios is most effective for improving comfort conditions (32%) and cooling periods (35%), while the structural properties of glazing units are most effective for reducing overheating periods (up to 12.2%). Another study by Bragança L, et al. [8] found that using Trombe walls and double self-cleaning glazing in the façade significantly reduces energy consumption and improves daylighting performance.

Studies conducted in Moroccan cities have provided practical insights into the performance of Trombe walls. For example, a case study by A. Mabrouki, et al. [3] found that incorporating Phase Change Materials (PCM) into a Trombe wall, with a 3 cm air gap, a 0.9 m sunshade, and RT 28 HC paraffin PCM (melting at 27–29°C), maintains indoor temperature and stores energy efficiently. This setup, suitable for a semi-oceanic climate, reduces annual energy consumption for a single-room house from 1285.6 kWh to 733.18 kWh, achieving a 42.97% savings. Z. Charqui, et al. [9] compared simulation results of three systems and found that the water Trombe wall with double glazing outperformed the others. It achieved an efficiency of 46% and exhibited thermal lag times of 4 hours and 49 minutes in winter and 7 hours and 23 minutes in summer. The water Trombe wall also reduced internal temperature variations by factors of 0.28 without solar film and 0.31 with the film.

The impact of shading and glazing types on the efficiency of Trombe walls is evident in their ability to reduce energy consumption and lower the carbon footprint of residential buildings. In Morocco, where solar energy is abundant, optimizing these elements can lead to significant environmental and economic benefits. Future research should focus on developing region-specific guidelines and exploring innovative materials and technologies to further enhance the performance of Trombe walls.

2 Methodology

2.1 Building description

The integration of Trombe walls into buildings, as visually represented in [Fig. 1], is crucial for enhancing energy efficiency, thermal comfort, and sustainability. By harnessing passive solar heating, Trombe walls reduce reliance on traditional heating systems, resulting in lower energy consumption and decreased carbon emissions.

Fig. 1. 3D view of a building integrated with a Trombe wall.

Each building component plays a critical role in ensuring the building's structural integrity, energy efficiency, comfort, and overall functionality, as summarized in [Tab. 1].

Table 1. Characteristics of the building components

Building	Component - Surface - U value
Occupied	Ground - 201,53 m² - 0,775 W/ m².K Roof - 201,53 m² - 0,746 W/ m².K Wall - 50,45 m² - 0,718 W/ m².K Wall - 48,93 m² - 0,718 W/ m².K Partition - 50,45 m² - 0,718 W/ m².K Wall - 48,93 m² - 0,718 W/ m².K Window - 6,31 m² - 1,960 W/ m². K
Trombe Wall (TW)	Ground - 6,24 m² - 0,775 W/ m².K Roof - 6,24 m² - 0,746 W/ m².K Partition - 50,45 m² - 0,718 W/ m².K Wall - 1,52 m² - 0,718 W/ m².K Wall - 50,45 m² - 0,718 W/ m².K Wall - 1,52 m² - 0,718 W/ m².K Window - 41,63 m² - … …

A Trombe wall with triple glazing replaces the traditional single or double glazing with an additional layer of glazing, creating two air gaps between the layers. This configuration enhances thermal insulation by further reducing heat loss and improving energy efficiency. The outermost layer allows solar radiation to enter and heat the thermal mass (typically masonry or concrete) inside the building, while the multiple glazing layers minimize heat transfer to the exterior and maintain a more stable indoor temperature.

As part of this investigation, we will conduct a thorough examination of different glazing configurations for a Trombe wall, as detailed in [Tab. 2].

Table 2. Characteristics of the Trombe wall glazing scenarios.

Glazing (Clear)	SHGC – Thickness - U value - Cost/m²
Single (SG 3)	0,861 - 3mm - 5,89 W/m². K - 120 €
Single (SG 6)	0,819 - 6mm - 5,78 W/m². K - 145 €
Double (DG 3-6)	0,762 - 3mm/6mm Air - 3,16 W/m². K - 177 €
Double (DG 6-6)	0,700 - 6mm/6mm Air - 3,10 W/ m². K - 184 €
Triple (TG 3-6)	0,682 - 3mm/6mm Air - 2,18 W/ m². K - 204 €
Triple (TG 3-13)	0,684 - 3mm/13mm Air - 1,76 W/ m². K - 220 €

The Trombe wall features local shading (LS) provided by a 1.0-meter overhang. This overhang helps reduce direct solar gain by shading the wall, thereby lowering the cooling load during hotter periods while still allowing for effective passive solar heating during cooler periods.

The Trombe wall utilizes dynamic window shading (DS) with transparent insulation. This shading system is positioned on the outside of the window and is controlled according to a predefined schedule. The dynamic shading adjusts based on the schedule to optimize solar gain and thermal performance, enhancing energy efficiency for heating and cooling throughout the year.

We integrate the Trombe wall into the overall HVAC system of the building as summarized in [Tab. 3].

Table 3. The overall HVAC status of the building.

Activity	Schedule
Occupancy (S-Occ)	Density: 0,030 people/m² Until: 07:00, 1, Until: 08:00, 0.5, Until: 09:00, 0.25, Until: 22:00, 0, Until: 23:00, 0.25, Until: 24:00, 0.75,
Heating (S-Heat)	COP: 2.50 Until: 09:00, 1, Until: 20:00, 0.5, Until: 24:00, 1,
Cooling (S-Coo)	COP: 2.50 Until: 09:00, 1, Until: 20:00, 0, Until: 24:00, 1,

The annual cooling and heating loads required to sustain a temperature within the thermal comfort range for the reference residential building are within the range of 20°C to 26°C, according to the Moroccan Thermal Construction Regulations.

2.2. Meteorological data

Each climatic region in Morocco is represented by a specific city, aiding in the understanding and adaptation of building design for thermal regulation according to the General Building Regulations in Morocco. This investigation will conduct an in-depth examination of Ifrane, representing Climatic Zone 4, which has a high energy demand for heating throughout the year. In contrast, the other five climatic zones primarily demand cooling energy, making the integration of Trombe walls ineffective in these regions. We acquired the meteorological data as depicted in [Fig. 2.3], using the Meteonorm software.

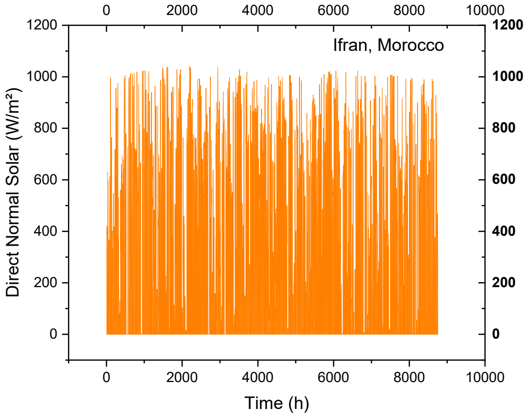

Fig. 2. Direct normal solar fluctuations in Ifran, Morocco.

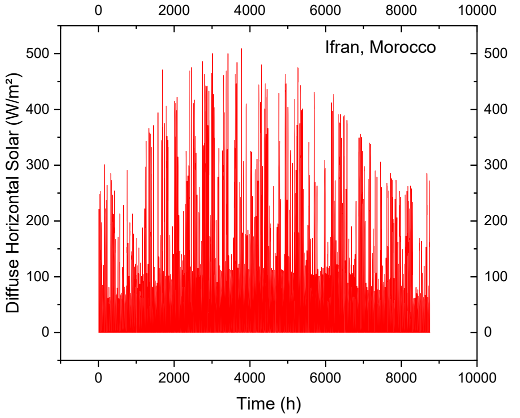

Fig. 3. Diffuse horizontal solar fluctuations in Ifran, Morocco.

Ifrane, Morocco, benefits from substantial solar energy potential, characterized by high levels of Direct Normal Irradiance (DNI) and notable Diffuse Horizontal Irradiance (DHI). The annual average DNI is significant, making it suitable for concentrated solar power systems, while DHI, though generally lower, supports photovoltaic systems by utilizing scattered sunlight. Seasonal variations influence these irradiance levels, with higher DNI during the summer due to clearer skies and increased DHI in winter owing to more cloud cover.

2.3 Physical model

The modeling and analysis of building structures, as well as simulations, were performed using the DesignBuilder software package. Wall simulations were carried out using the Conduction Transfer Functions (CTFs) method, which is a state-space approach utilized in EnergyPlus. Moreover, for the exterior surface, we employed the DOE-2 convection algorithm, while for the interior surface, we utilized TARP.

The fundamental formulations of the thermal model in mathematical terms rely on heat transfer balances. The equation concerning the exterior wall surface is illustrated in [Eq. 1],

$$Q_{\mathrm{solr}} + Q_{\mathrm{LWR}} + Q_{\mathrm{conv}} + Q_{\mathrm{cond}} = 0 \quad (1)$$

where Q_{solr} denotes the heat flux attributable to both direct and diffuse solar radiation, characterized by short wavelengths, Q_{LWR} represents the net exchange of the flux of long-wave (thermal) radiation interacting with the ambient air and environment, Q_{conv} indicates the exchange of convective flux with the ambient outdoor air and Q_{cond} represents the heat flux due to conduction into the exterior wall.

The thermal equilibrium within the indoor environment is governed by the equation provided in [Eq. 2],

$$Q_{\mathrm{LWX}} + Q_{\mathrm{SW}} + Q_{\mathrm{LWS}} + Q_{\mathrm{sol}} + Q_{\mathrm{conv}} + Q_{\mathrm{cond}} = 0 \quad (2)$$

where Q_{LWX} denotes the net exchange flux of long-wave (thermal) radiation among the surfaces within the indoor environment, Q_{SW} represents the overall flux of short-wave radiation reaching surfaces from sources of illumination, Q_{LWS} denotes the radiation flux emitted by equipment within the designated area, Q_{cond} represents the heat conduction flux traversing through the interior wall, Q_{sol} denotes the solar radiation flux absorbed by the surfaces and Q_{conv} represents the convective heat flux toward the indoor air.

D. B. Crawley et al. have documented and validated the individual operations of these equations [10]. The energy used by the heat pump condenser in both cooling and heating modes is determined by the coefficient of performance (COP) specified in [Tab. 3]. This calculation relies on the individual operations of the equations is documented and validated by Richard Raustad [11].

3 Results and discussions

The presented results focus on the carbon dioxide (CO2) emissions associated with electricity usage for heating and cooling in a residential building integrated with a Trombe wall located in Ifran, Morocco. This analysis considers various glazing and shading scenarios.

3.1. Glazing impacts

Based on [Fig. 4], among the configurations tested, the Triple Clear (TG 3-13) glazing emerged as the most effective, achieving a significant 22.5% annual decrease in CO_2 emissions compared to a building without a Trombe wall. This glazing type excels due to its superior thermal insulation properties, which minimize heat loss in winter and heat gain in summer while allowing optimal solar energy absorption. The result is enhanced energy efficiency, reducing the building's reliance on external heating and cooling systems and thereby lowering CO_2 emissions. This finding underscores the critical role of glazing selection in optimizing Trombe wall performance and contributing to sustainable building practices in Moroccan climates.

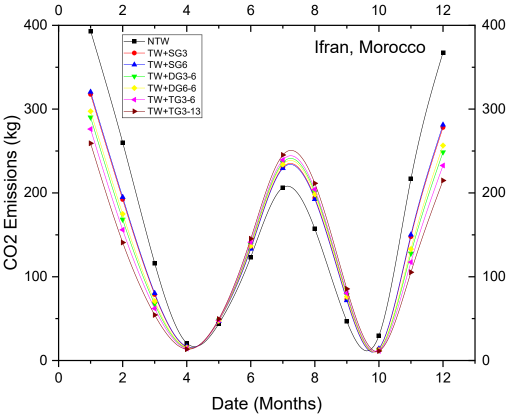

Fig. 4. Effects of glazing on CO2 emissions.

3.2 Local shading impacts

According to [Fig. 5], implementing local shading for various glazing types leads to a 4.5% increase in annual CO_2 emissions compared to the same glazing without local shading.

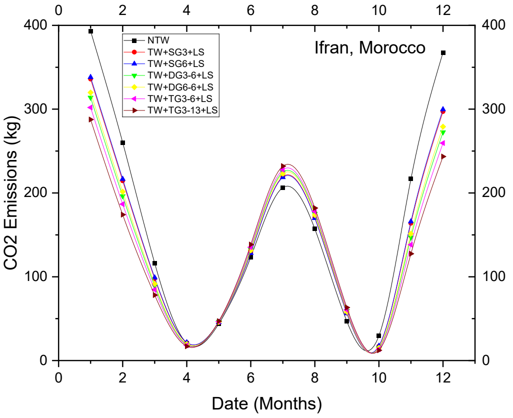

Fig. 5. Effects of local shading on CO2 emissions.

This outcome can be attributed to the reduction in solar energy absorption caused by shading, which diminishes the Trombe wall's ability to effectively utilize solar heat for passive heating purposes. In Ifran's climate, where solar gain is critical for reducing heating demands during colder months, excessive shading can inadvertently increase the need for supplementary heating, thereby raising overall energy consumption and associated carbon emissions. These findings underscore the importance of carefully balancing shading strategies with glazing properties to optimize the energy efficiency and environmental performance of Trombe walls in varying climatic conditions and building designs.

3.3 Dynamic shading impacts

Based on [Fig. 6], Results reveal that implementing dynamic window shading under this controlled operation reduces annual CO₂ emissions by 2% compared to the same glazing without dynamic shading. This reduction is attributed to the shading system's ability to optimize solar heat gain during daylight hours while minimizing heat loss during colder periods, thereby reducing the need for additional heating energy. The findings underscore the effectiveness of scheduling dynamic shading to enhance the energy efficiency of Trombe walls, particularly in climates like Ifran's where solar gain is critical for passive heating. Integrating such shading strategies with high-performance glazing materials can significantly contribute to lowering carbon emissions associated with building operations, promoting sustainable building practices tailored to local environmental conditions.

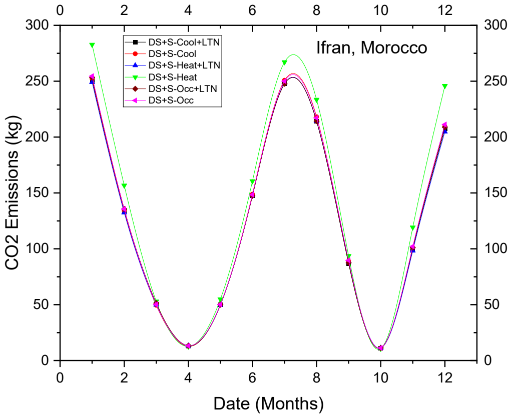

Fig. 6. Effects of window shading on CO2 emissions.

3.4 Combined impacts

According to [Fig. 7], findings demonstrate that combining dynamic window shading (DS) and Triple Clear (TG 3-13) glazing in a residential building featuring a Trombe wall in Ifran, Morocco, resulted in a significant decrease of up to 37% in CO2 emissions linked to electricity usage during heating days. Additionally, it led to a reduction of up to 24% in CO2 emissions associated with electricity usage for both heating and cooling purposes in the same residential building context in Ifran, Morocco.

The Triple Clear glazing likely enhanced thermal insulation, minimizing heat loss and reducing the need for supplemental heating. Meanwhile, DWS effectively controlled solar heat gain, optimizing indoor thermal comfort and reducing the reliance on active cooling systems. These combined strategies improved overall energy efficiency by reducing electricity demand for heating and cooling, thereby significantly lowering the environmental impact in terms of CO2 emissions.

The results underscore the practical benefits of integrating advanced glazing technologies and adaptive shading systems in residential buildings, particularly in climates like Ifran's, to achieve substantial reductions in carbon footprint while enhancing building performance and occupant comfort.

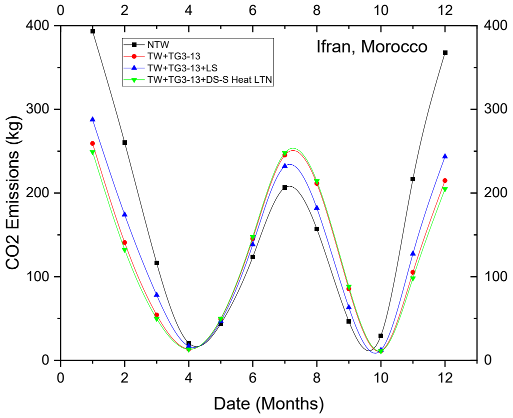

Fig. 7. Combined effects on CO2 emissions.

3.5 Economic impacts

Double and triple glazing provide enhanced insulation compared to single glazing, reducing heat loss but costing more upfront.

Table 4. Cost of shading and glazing types of Trombe wall.

Cost (€)	Glazing - Glazing+LS - Glazing+DS
Single (SG 3)	4995,6 - 8034,5 - 7495,6
Single (SG 6)	6036,3 - 9075,2 - 8536,3
Double (DG 3-6)	7368,5 - 3038,9 - 9868,5
Double (DG 6-6)	7659,9 - 10698,8 - 10159,9
Triple (TG 3-6)	8492,5 - 11531,4 - 10992,5
Triple (TG 3-13)	9158,6 - 12197,5 - 11658,6

As summarized in [Tab. 4], while these glazing options can be a worthwhile investment for maximizing energy savings, integrating dynamic shading systems in residential buildings, especially in Ifrane, representing Climatic Zone 4, offers practical benefits. These dynamic shading systems not only help significantly reduce the carbon footprint but also lower construction costs compared to traditional local shading solutions.

4 Conclusion

This study comprehensively examines the impact of glazing and shading configurations on CO_2 emissions associated with heating and cooling in a residential building integrated with a Trombe wall in Ifran, Morocco.

The findings underscore the critical role of glazing selection in enhancing energy efficiency and reducing carbon emissions. Specifically, Triple Clear (TG 3-13) glazing emerged as highly effective, achieving a substantial 22.5% annual decrease in CO_2 emissions compared to buildings without Trombe walls. This glazing's superior thermal insulation properties minimize seasonal heat loss and gain while maximizing solar energy absorption, thereby reducing reliance on external heating and cooling systems. Conversely, implementing local shading for the same glazing type was found to increase CO_2 emissions by 4.5% annually due to reduced solar heat absorption, emphasizing the need for balanced shading strategies tailored to local climate conditions. Furthermore, dynamic window shading controlled by a predefined schedule demonstrated a 2% annual reduction in CO_2 emissions compared to static glazing setups. This approach optimizes solar heat gain during daylight hours and minimizes heat loss at night, effectively lowering overall heating demands.

These results highlight the importance of integrating dynamic shading strategies with high-performance glazing to optimize Trombe wall performance and promote sustainable building practices in diverse climatic settings like Ifran. By implementing these findings, stakeholders can significantly contribute to reducing carbon footprints and advancing environmental sustainability in building design and operation.

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