Towards Sustainable Building Materials: Review and Numerical Study of composite wall with Bio-Based Phase Change Materials under the Climate of Fez

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Abstract. The increase in global energy demand and reliance on fossil fuels exacerbate environmental problems, reinforcing the need to adopt sustainable solutions. Biobased phase change materials (BPCMs) offer an eco-friendly alternative to conventional PCMs due to their ability to store and release thermal energy in the form of latent heat. This study combines a comprehensive literature review with a numerical simulation developed in Python, applied to the climatic conditions of Fez (Morocco). The results show that integrating RT20 and $CaCl_2 \cdot 6H_2O$ into building walls can reduce indoor thermal fluctuations by approximately 28%, increase the thermal lag by 3.4 hours, and decrease cooling demand by around 7%. These performances confirm the high potential of biobased BPCMs to improve thermal comfort, reduce energy consumption, and support the transition to sustainable buildings adapted to hot and dry climates.
Keywords—Phase Change Materials, Bio-based, latent heat, Thermal energy storage, Thermal comfort, Building envelopes, Hot climate, Numerical simulation, CFD Model.

1. INTRODUCTION

The development and implementation of fully sustainable energy storage systems is essential to integrate renewable energy sources into an already energy-conscious society. This priority is driven by economic growth, the need to build sustainable infrastructure, and a heightened awareness of the technological effects on climate change. The ability of companies to contribute to sustainability directly influences their market value, as consumers demand a reduction in the environmental impacts of global industries. To build a sustainable future, dominant technologies must not be based on scarce, exhaustible or toxic materials and must be economically viable. Thus, it is crucial to research and develop eco- friendly and low-cost alternatives to energy storage in electric batteries. One of the major contributions to future sustainability is the exploration of the use of bio-based materials in energy storage systems, whether existing or under development. To assess the potential impact of these materials, it is necessary to consider not only their origin, but also the entire supply chain, the required chemical modifications, stabilization pathways, compatibility, waste management, recyclability, as well as environmental and societal health impacts. Global energy consumption is increasing significantly, with the construction sector accounting for more than 30% of energy needs in many countries. As energy rationalization becomes a global priority, its environmental impact, especially in terms of greenhouse gas emissions and global warming, is becoming increasingly evident. As a result, reducing energy consumption in the building sector has become a necessity and a government obligation. Many passive and active solutions are continuously offered and improved. One passive approach is to integrate phase change materials (PCMs) into building envelopes to improve their heat storage capacity. Beyond the building sector, PCMs have also shown great potential in other energy-related applications, particularly in seawater desalination systems. Recent bibliometric studies have revealed a strong increase in research and implementation of PCMs in desalination processes over the past few years, highlighting their role in enhancing thermal energy recovery and improving the efficiency of solar desalination technologies [1]**.** Phase change materials (PCMs) are classified into organic, inorganic, and eutectic, each with its advantages and limitations. Organic PCMs are chemically stable, but have low latent heat capacity and are flammable, while inorganic PCMs offer high heat capacity but suffer from thermal instability. To improve the energy efficiency of buildings, PCMs can be integrated into building materials in the form of layers, composites or microcapsules. Thermal energy storage (TES) technology allows heat to be conserved and released according to energy needs, using three methods: latent heat storage (LHS), sensitive heat storage (SHS) and thermochemical heat storage (THS) [2]. For thermal energy storage (TES), phase change materials (PCMs) are used for latent heat storage (LHS). These PCMs include inorganic, organic, and eutectic materials. Of the organic PCMs (OPCMs), fatty acids, paraffin waxes and polyethylene glycol (PEG) are the most commonly used. Although PCMs are effective for energy conservation, their frequent use can disrupt ecosystems, including by consuming valuable natural materials. Bio-based PCMs among the

OPCMs are considered to be the most environmentally friendly and economical. They come from renewable and recyclable resources, such as agri-food and biomass waste. BPCMs include materials such as soybean oil, palm oil, palm kernel oil, coconut oil, and animal fat. According to the literature, the use of BPCMs has many advantages over other types of PCMs, including reducing environmental impacts, promoting sustainability, and reducing the carbon footprint. In contrast, petroleum- based PCMs, such as paraffin, contribute to global warming due to their dependence on fossil fuels and indirect combustion. In addition, Wissal et al. [3] recently demonstrated through a bibliometric analysis that artificial intelligence (AI) has become a major research focus in the field of phase change materials for building applications. Their study, based on data extracted from the Scopus database, revealed a growing trend toward the use of AI to model, predict, and optimize the thermal performance of PCMs. This evolution highlights the increasing integration of intelligent computational tools in the design of next-generation energy-efficient materials.

This paper provides a detailed overview of the different categories of BPCMs, thermal energy storage (TES) technologies, and integration methods. As illustrated in Figure 1, there are many variables that need to be considered to optimize these materials and technologies. By examining the performance data of BPCMs, as well as their chemical composition, thermophysical properties, benefits and challenges, the potential of incorporation techniques will be explored. This analysis covers the incorporation methods that are essential for creating effective energy-saving systems in buildings. It will also facilitate the selection of appropriate BPCM blending technologies for specific heat storage applications in buildings. This article offers a twofold contribution: (i) an updated literature review on bio-based phase change materials (BPCM) and their applications in the building sector, and (ii) a numerical simulation developed in Python, applied to the climate of Fez, a city characterized by significant summer temperature variations. This combined approach illustrates the real relevance of BPCM in a local context, while relying on results from international research.

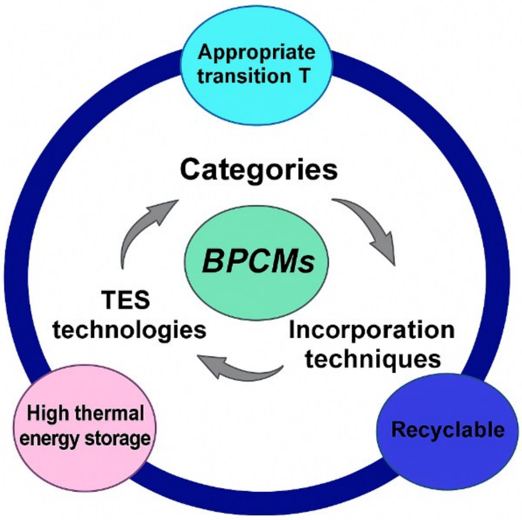

Fig. 1. TES technologies and techniques for incorporating BPCMs.

2. BIOBASED PHASE CHANGE MATERIALS

Hundreds of bio-based PCMs have already been presented in the literature, and there are potentially several thousand that have not yet been studied, either in the general literature or specifically in the context of SSA. The majority of existing studies focus on fatty acids (since the early 1980s) and fatty acid esters (which have attracted increasing interest since the 2010s) as potential PCMs [4]. Sugar alcohols have also been the focus of research over the past ten years, along with other compounds like alcohols. Each class of these materials has distinct thermophysical characteristics and properties due to their overall chemical structures and thermodynamic stability. Section 2 summarizes the results of the published studies and examines the most important characteristics of the different classes of bio- based materials, focusing on both pure PCMs and pure PCM blends without the inclusion of additives or other types of phases. An overview of the studies reviewed is presented and analyzed in the following paragraphs.

Bio-based PCMs, with a low carbon footprint, are a cost-effective alternative to traditional organic PCMs. Made from natural oils rich in fatty acids, they can be modified to achieve specific thermal properties. However, their thermophysical characteristics and integration into buildings require careful design to ensure optimal performance, whether passively or actively integrated [5].

3. CATEGORIES OF PHASE CHANGE MATERIALS

As illustrated in Figure 2, PCMs can be classified into three categories: organic, inorganic, and eutectic, based on their chemical composition. To optimize the thermal performance, design, and energy efficiency of buildings, ideal PCMs should possess the following properties: (1) an appropriate phase change temperature (18-30 °C); (2) good heat transfer capabilities, thus minimizing the space needed in the building structure and allowing for efficient generation, storage, and release of a large amount of melted heat; (3) time-stable thermal performance, with no or low subcooling; (4) good economic feasibility. Organic eutectic polyols, fatty acids, esters and PCMs derived from vegetable oils and animal fats will be discussed in detail [6].

3.1 Polyols

Polyols can be classified into three categories: sugar alcohols, low molecular weight polyols, and polymeric polyols. Some polyols also have notable drawbacks. For example, inositol is chemically unstable, D- mannitol reacts with oxygen and is chemically unstable, and galactitol has low ring stability. However, some candidates have shown great potential. For example, erythritol has a very high latent heat storage capacity (more than 300 J/g) [7]. Lauryl alcohol is suitable for direct use in construction due to its low phase transition temperature (24 °C).

3.2 Fatty acids

Fatty acids such as myristic acid, stearic acid, and lauric acid are BPCMs suitable for thermal energy storage (TES) applications. These acids come from renewable plant and animal sources. Animal fats and vegetable oils contain more than 97% C16 and C18 fatty acids. Unlike paraffin, fatty acids are not derived from fuel, making them less sensitive to fluctuations in crude oil prices. As a result, CMBPs provide a continuous, non- polluting source of supply. Fatty acids are characterized by the general formula $CH_3(CH_2)_{2n}COOH$. They are suitable as TES materials due to their low volume variation, lack of supercooling and high latent heat. These characteristics make fatty acids particularly suitable for use in buildings to save energy [8] .

3.3 Esters

Esters make up an important part of BPCM. Depending on their origin, esters can be classified into two categories: those derived from vegetable oils and animal fats, and those produced by esterification of acids and alcohols of biological origin. Although these BPCMs can be used directly in the construction of TES, they have shortcomings in terms of flame retardants and thermal conductivity. Fabiani et al. [9] studied expired palm oil from the food industry, finding that it offered strong thermal stability, low health risks, and fewer leakage issues according to life cycle analysis, making it a promising material for potential TES applications. Boussaba et al. [10] added non-cocoa vegetable fat recovered from the confectionery industry to a mineral panel composed of natural clay and cellulose fiber. The results of more than 2000 tests confirmed that the vegetable fat composite BPCM possessed high thermal and chemical stability, although the introduction of vegetable fat slightly reduced the compressive strength of the carrier material. Sari et al. [11] used a mixture of erythritol tetra palmitate, erythritol tetra stearic acid, diatomite, and expanded perlite to prepare a composite BPCM based on fatty acid esters. Serrano et al. [12] introduced a vegetable oil methyl ester BPCM into gypsum board, finding that gypsum containing BPCM had superior thermal insulation properties compared to gypsum without BPCM. These studies show that esters have excellent potential for the construction of TES.

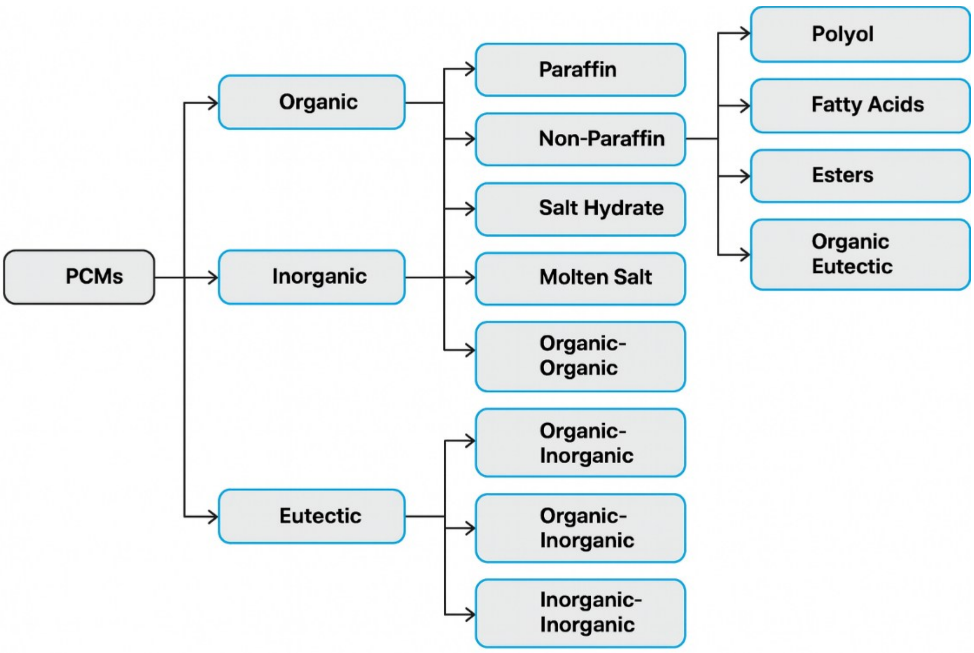

Fig. 2. Categories of PCMs [2].

3.4 Eutectics

Current research on pure bio-based phase-change materials shows that it is essential to ensure a stable combination between the PCM and the support material. Although this research is relatively straightforward, few pure BPCMs can meet the requirements of TES for construction due to their high phase transition temperature and high cost. Therefore, researchers studied eutectic BPCMs using binary or multiple phase change systems. A eutectic mixture is a specific composition of two or more materials with different melting temperatures. The melting temperature of the eutectic mixture is lower than that of each of the individual phase change materials that make up the mixture. However, when selecting materials for the preparation of eutectic BPCMs, it is crucial to consider compatibility between phase- change materials. Some BPCMs suitable for low- temperature construction applications have been developed, and more complex multiphase changeover systems have been explored and studied [13].
In summary, fatty acids are representative examples of non-paraffinic waxes used as phase change materials (PCMs). They are widely studied due to their high latent phase change heat, lack of supercooling, stableproperties and environmental friendliness. However, fatty acids exhibit a slight corrosiveness, and their compatibility with carrier materials should be considered when applying them. Esters, derived from fatty acid esters, offer similar benefits to fatty acids. Polyols receive less attention due to their higher phase transition temperature range and tendency to supercool. Eutectic BPCMs possess an appropriate phase transition temperature (18-30 °C), high latent phase transition heat, and low cost, making them particularly suitable for architectural applications. However, due to their organic characteristics, all BPCMs have a low thermal conductivity, thus constituting a major disadvantage limiting their application.

The manufacturing methods of bio-based phase change materials (BPCMs) fall into two main categories: direct incorporation and indirect incorporation. Direct incorporation methods include immersion, absorption, use of recyclable waste, and integration into an economic framework. The easiest method is to use used cooking oils, fatty acids, and beeswax to create a low- cost biodegradable composite. These materials are readily available and make it possible to manufacture effective PCMs in an economical and environmentally friendly way.
Indirect incorporation methods, on the other hand, include microencapsulation, temperature ration, shape-stable encapsulation, and shape-like encapsulation. Microencapsulation and temperature ration are particularly used to prevent BPCM leakage, thanks to their flexibility, large surface area, thermal stability, and corrosion resistance. These techniques allow the containment of the PCMs while maintaining their optimal thermophysical properties. BPCMs are widely studied and considered for low- carbon thermal energy storage (TES) applications. They have several advantages: renewable vapor pressure, low explosiveness, environmental compatibility, wide range of melting temperatures, controlled flammability, chemical stability, high density, and recyclable nature. These characteristics allow them to be used in various applications, especially in buildings. In addition, the abundant availability and low cost of PCMs make them attractive alternatives to conventional PCMs. Due to their advantageous properties, PCMs are preferred for many applications, as illustrated in Figure 3. These materials offer a promising solution for sustainable and efficient energy storage [14].

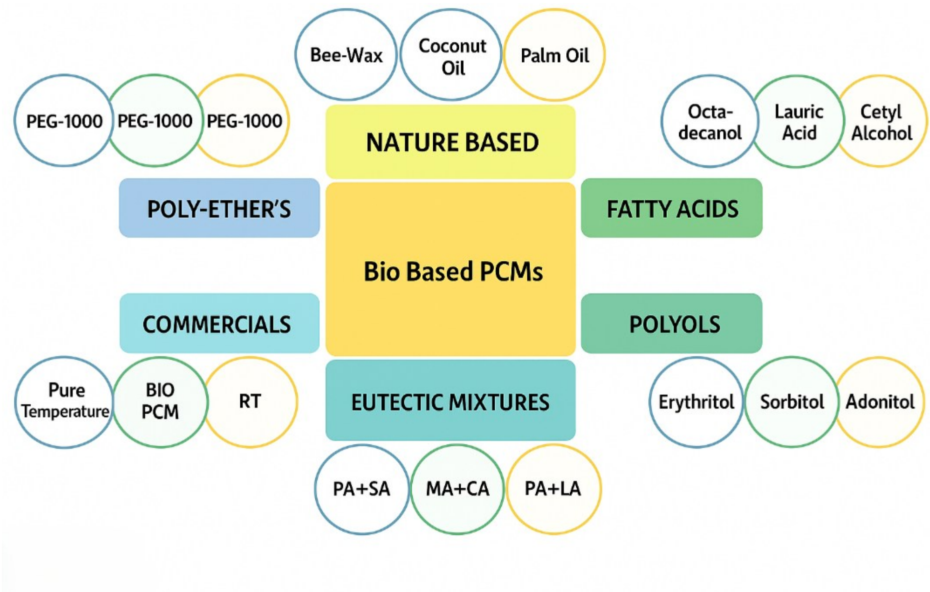

Fig. 3. Types of biobased PCMs [14]

4 METHODS OF INTEGRATING PCMs

Traditional BPCMs, such as vegetable oils, animal fats, and fatty acids, have respectable thermal energy storage (TES) characteristics. Currently, most of these materials are biodegradable and are used in various applications as biodegradable PCMs. Triesters, also known as triglycerides, consist of three long-chain fatty acids and are found in animal fats and vegetable oils. The agricultural and food industries produce unconventional BPCMs that are not yet standardized, including animal fat waste, inedible oils such as those from chicken feathers, lard and tallow. These materials are used in TES because of their fatty acid content and good thermal properties. A few preliminary studies have explored the use of used edible oils, biolubricants, bio- based solvents for pollutants, and 2nd generation biofuels/gases. In TES applications, PCMs have demonstrated remarkable properties through various integration techniques, such as direct incorporation, indirect incorporation, and the use of recycled waste. Methods such as immersion, absorption, temperature ration, microencapsulation, and shape stabilization play a crucial role in minimizing the degradation of BPCM matrices. Techniques such as ultrasonication, direct immersion, vacuum impregnation, and various forms of encapsulation are illustrated in Figure 4. Microencapsulation is commonly used for BPCM, but it is important to select the best potting materials to optimize production costs [15].

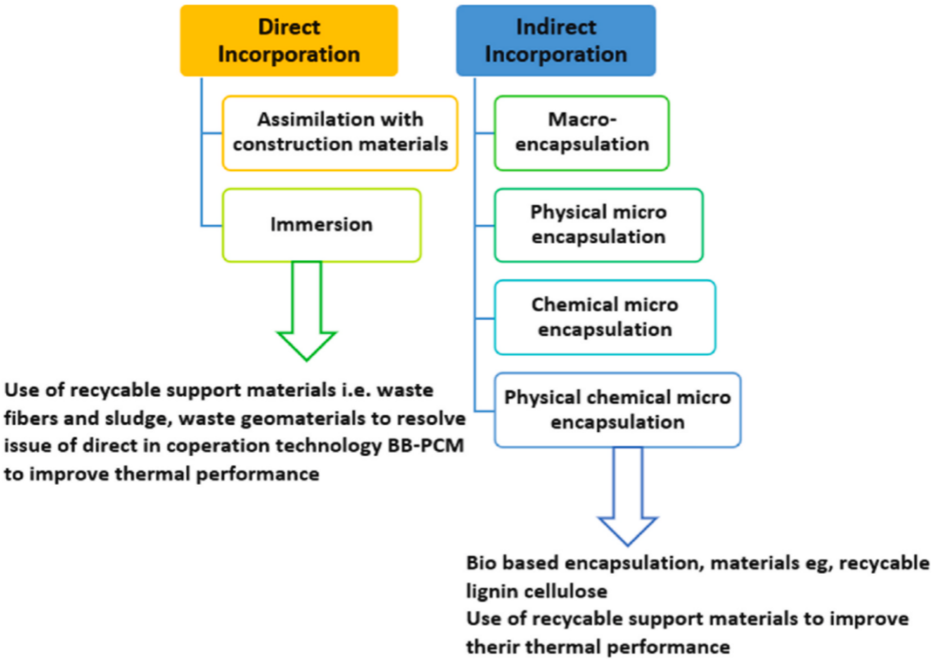

Fig. 4. Techniques for Incorporating BPCMs: Direct and Indirect Methods [15]

4.1 Direct incorporation

Direct incorporation is the simplest and most economical method of using BPCMs, as it requires less labour and industrial infrastructure. This method involves directly mixing BPCMs with building materials such as gypsum and concrete, making it easier to use them for energy storage. Cellat et al. [16] showed that adding butyl stearate and BPCM directly to concrete made TES more cost-effective and improved the durability and lifespan of concrete. However, an excessive amount of PCMs can reduce the compressive strength of concrete. In addition, concrete, being alkaline, may not be compatible with many PCMs, requiring the selection of appropriate impregnating agents. Feldman et al. [17] found that the addition of 21-22% butyl stearate to gypsum board did not significantly affect its flexural strength, while significantly increasing its heat storage capacity.

4.2 Encapsulation

According to this technology, the BPCMs are encapsulated before being integrated into building products to prevent leaks during the liquid phase. The container of the BPCM must have high mechanical strength, good flexibility, strong corrosion resistance, stable structure and thermal performance, as well as a large enough surface area for heat transfer. Although the cost of this technology is currently high and the preparation process is complex, it is still acceptable given the market demand for BPCM and future environmental benefits. The two main encapsulation methods are microencapsulation and microencapsulation [18].

4.3 Macroencapsulation

Encapsulation consists of introducing BPCMs into panels, bags, tubes, cubes or other large containers, usually with a diameter greater than 1 mm. This technique makes it possible to combine a large quantity of BPCM in a single container. Key benefits include ease of transport and recycling, packaging designed specifically for the intended application, and improved material compatibility. Since BPCMs are not directly mixed with the matrix material (such as gypsum, mortar, concrete, or polymer), degradation of the mechanical properties of the matrix material is avoided [19].

4.4 Microencapsulation

In the microencapsulation process, small solid or liquid particles or droplets of BPCM, constituting the core, are surrounded or covered with a continuous film (shell) of high molecular weight polymer material, to produce microcapsules ranging in size from nanometer to millimeter. This technique allows for a controlled release of thermal energy, prevents material exchange with the environment, prevents degradation during heat absorption/release cycles, and increases the surface area and thermal conductivity of the capsules. It is crucial to control the thickness of polymer capsules containing BPCM. A shell that is too thick reduces the proportion of PCMs in the final product and hinders heat exchange, while a shell that is too thin will not retain the PCMs in the capsule. Depending on the particle size and manufacturing process, the mass ratio of microencapsulated PCMs ranges from 50% to 90%. In addition, the shell material should not chemically react with the matrix material if it is incorporated into the microcapsule [20].
Recent advancements and Comparative Analysis on BPCMs

The papers studied highlight various experiments carried out to develop and characterize bio-based PCMs for thermal storage applications in buildings. This work focuses on the fabrication of phase change materials, thermal characterization and structural stabilization. The bio-based PCMs studied are mainly made from natural materials such as vegetable oils and beeswax. In the study by Guermat et al. [21], a mixture of beeswax and local vegetable oils was used to develop a PCM with eco-friendly properties. Similarly, Erkizia et al. [22] features a microencapsulated MCP, PureTemp25, designed for easy integration into building materials. Finally, in the study of Ju et al. [23] SiO_2-coated cenosphere- stabilized PCMs have been developed to prevent material leakage during phase changes.

4.4.1 Thermal characterization

Advanced thermal characterization techniques were employed to evaluate the performance of the PCMs. In the study by Guermat et al. [21], differential scanning calorimetry (DSC) was used to measure the melting temperature and latent heat, revealing high heat storage capacities for bio-based PCMs. The study by Erkizia et al. [22] also used DSC assays to analyze the PureTemp25 samples, while Ju et al. [23] supplemented their thermal evaluations with conductivity analyses to optimize the heat transfer capacity of the composite materials.

4.4.2 Stabilization and Encapsulation Techniques

The integration of PCMs into building materials poses stability challenges, especially to prevent leaks. To address these issues, several stabilization methods have been tested. In the study by Ju et al. [23], researchers used SiO_2-coated cenospheres to encapsulate the PCMs, preventing leaks and increasing thermal durability. In the study by Erkizia et al. [22], the addition of reduced graphene improved thermal conductivity, facilitating the rapid storage and release of heat.

5. Description of the studied configuration

In the context of traditional construction practices in Morocco, walls are mainly made of brick and mortar, which are common materials but offer limited performance in terms of thermal inertia. Under the hot and dry climate of Fez, where summer temperatures can exceed 40 °C, these walls quickly absorb and transmit heat to the interior, leading to a significant increase in indoor temperature and a deterioration of thermal comfort.
To address this issue, the present study focuses on the integration of bio-based phase change materials (BPCM) into exterior walls. These innovative materials have the ability to store and release heat in the form of latent heat, which helps to smooth temperature variations and enhance the building's thermal inertia.
Figure 1 illustrates the four wall configurations studied: Figure 1(a): Reference wall, composed solely of brick and mortar, representing the classic structure of buildings in the region. Figure 1(b): Wall with BPCM1 (RT20) — a 2 cm

layer of RT20 is added on the outside to absorb heat during the morning temperature rise. Figure 1(c): Wall with BPCM2 ($CaCl_2 \cdot 6H_2O$) — a 2 cm layer of this material is placed on the exterior side to act during hours of high solar radiation, thanks to its higher melting temperature. Figure 1(d): Combined wall (BPCM1 + BPCM2) — the two layers are stacked, allowing sequential action: BPCM1 acts in the first phase in the morning, while BPCM2 takes over during the afternoon thermal peak.

This approach aims to evaluate the effect of each configuration on reducing transmitted heat flux, delaying the timing of heat peaks, and stabilizing the indoor temperature. The thermophysical properties of the materials used are summarized in Table I, which serves as a basis for comparing the energy performance of the different configurations studied.

Table 1. Thermophysical properties of the materials used in the study

Materials	Thermal conductivity (W/m·K)	Density (kg/m³)	Specific heat (J/kg·K)	Melting temperature (°C)	Latent heat (kJ/kg)
Brick	0.925	920	2100	–	–
Mortar	0.97	840	1600	–	–
PCM1 (RT20)	0.20	870	1800	20	179
PCM2 ($CaCl_2 \cdot 6H_2O$)	0.43	1515	1900	26	150

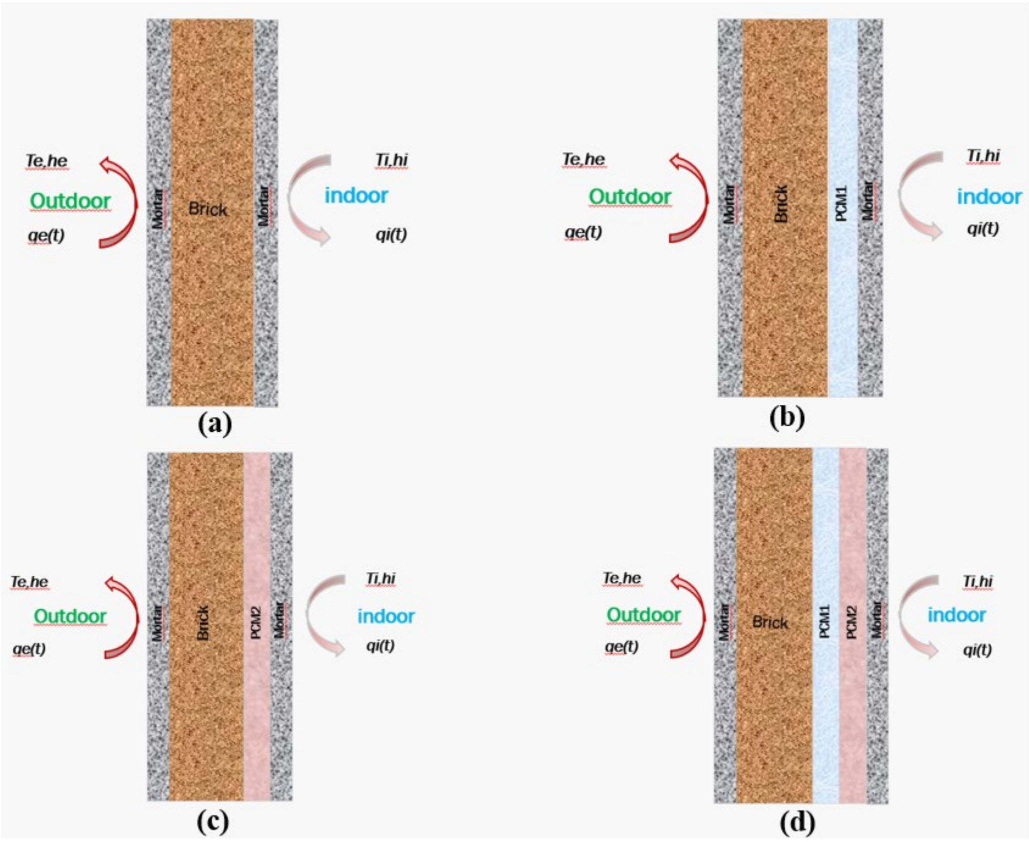

Fig. 5. Configuration of the Wall: (a) Reference, (b) With PCM1, (c) With PCM2, (d) Wall including two types of parallel PCM.

6. Weather Analysis

Fez, located at a latitude of 34.018° and a longitude of -5.007°, with an altitude of approximately 415 meters above sea level, is about 180 kilometers east of Rabat, Morocco, and about 200 kilometers from the Atlantic Ocean. The city enjoys a Mediterranean climate with continental tendencies, characterized by cool, wet winters and hot, dry summers. The temperature differences between day and night can be significant, often reaching more than 15°C during the summer. The average annual temperature in Fez is about 17 to 18°C.

Figure 6 illustrates the annual climate data for the city of Fez, obtained from the NASA POWER API database for the year 2024. It is observed that the winter months (January, February, December) are the coldest, with minimum temperatures close to 6 °C in January and relatively low solar irradiation, varying between 11 and 14 kWh/m². In contrast, the summer period (June, July, August) is distinguished by maximum temperatures exceeding 40 °C, with a marked peak in July, the hottest month, where the average temperature reaches about 30 °C and the solar radiation approaches 28 kWh/m². Between April and July, the average temperature gradually increases from about 12 °C in April to over 20 °C in July, before decreasing starting from September. The seasonal transition highlights significant differences between maximum and minimum temperatures, characteristic of a Mediterranean climate with continental tendencies. These differences can exceed 20 °C in summer, reflecting high daily thermal amplitudes. Thus, the climate of Fez is characterized by cool and humid winters and particularly hot and dry summers, conditions that justify the integration of passive thermal regulation solutions, such as the use of bio-sourced phase change materials (PCM), to improve indoor comfort and reduce energy consumption in buildings.

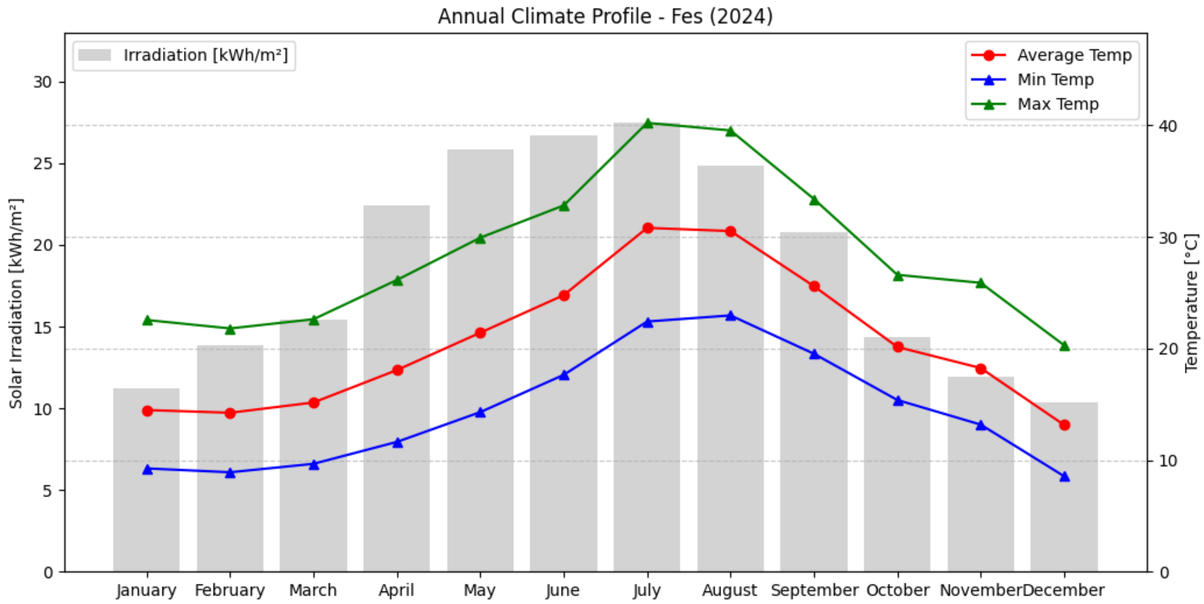

Fig. 6. Climate data from the Fez region (2024)

7. Numerical Approach

To determine the thermal performance of the four wall configurations, the temperature profile through the different layers was calculated by numerically solving the energy equation using the CFD (Computational Fluid Dynamics) method (Eq. 1). The study was conducted for a south-facing wall located in Fez (Morocco), subjected to real summer climatic conditions from the NASA POWER API database for the period of July 23 to 24, 2024. The Perez model was used to determine the solar radiation flux incident on the external surface of the wall.

$$\rho_j C_{p,j}\frac{\partial T_j}{\partial t} = \lambda_j\frac{\partial^2 T_j}{\partial x^2} + \lambda_j\frac{\partial^2 T_j}{\partial y^2} \qquad (1)$$

where j represents the layer number (j = 1, 2, …, N). This equation is applicable for completely solid or liquid materials. However, in order to accurately model the thermal behavior of phase change material (PCM) during melting and solidification processes, an additional term (Eq. 2) is added to account for the latent heat of fusion:

$$\rho_j C_{p,j}\frac{\partial T_j}{\partial t} = \lambda_j\frac{\partial^2 T_j}{\partial x^2} + \lambda_j\frac{\partial^2 T_j}{\partial y^2} - \rho_j L_f\frac{\partial f_l}{\partial t} \qquad (2)$$

where Lf is the latent heat of fusion (kJ/kg) and fl is the liquid fraction of the PCM, defined as follows:

$$f_l = \begin{cases} 0, & T < T_{fusion} \\ [0-1], & T = T_{fusion} \\ 1, & T > T_{fusion} \end{cases} \qquad (3)$$

The boundary conditions take into account combined radiative and convective heat transfers on the external surface, as well as convective transfer on the internal surface, as expressed in equations (4) and (5). The other faces of the configuration are considered adiabatic, as indicated in equation (6).

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$$-\lambda_1 \left(\frac{\partial T}{\partial x}\right)_{x=0} = h_e\left(T_{sa}(t) - T_{x=0}(t)\right) \quad (4)$$

$$-\lambda_N \left(\frac{\partial T}{\partial x}\right)_{x=L} = h_i\left(T_{x=L}(t) - T_{in}\right) \quad (5)$$

$$\frac{\partial T(x,0,t)}{\partial y} = \frac{\partial T(x,H,t)}{\partial y} = 0 \quad (6)$$

Where h_i and h_e represent the convective heat transfer coefficients at the inner and outer surfaces of the wall, set at 9 W/m²·K and 22 W/m²·K, respectively. The indoor temperature_inis assumed to be constant and equal to 27 °C, while the air-solar temperatures(t) combine the effect of solar radiation and the outdoor temperature:

$$T_{sa}(t) = T_a(t) + \frac{\alpha_s I_s(t) - \varepsilon\sigma(T_a^4(t) - T_{sky}^4(t))}{h_e} \quad (7)$$

In the context of weather data for the Fez climate zone, several parameters were considered to evaluate the air-solar temperature:

$Ta(t)$ represents the outdoor air temperature obtained from the NASA POWER database,

αs is the solar absorption coefficient of the wall surface,

$Is(t)$ the global incident solar radiation (W/m²),

ε the surface emissivity,
and
$\sigma = 5.67 \times 10^{-8}$ W/m²·K⁴ is the Stefan–Boltzmann constant.

The simulated air-solar temperature for the period from July 23 to 24, 2024, is presented in Figure 8. These results provide valuable information on the actual thermal conditions in Fez, allowing for the analysis of the combined effects of outdoor temperature, solar radiation, and the thermophysical properties of bio-based PCMs on the thermal response of the south-facing wall during the hottest days of summer.

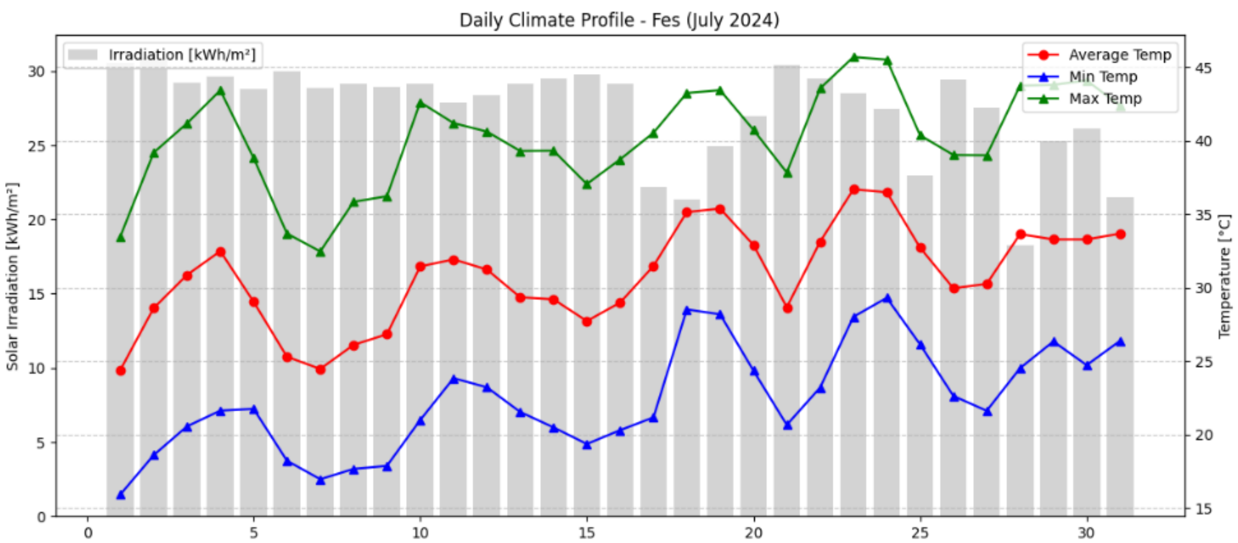

Fig.7. Daily climate data for Fez for July 2024 from the NASA POWER API.

Figure 7 presents the daily climatic profile of the city of Fez during the month of July 2024, based on weather data provided by the NASA POWER API. There is a significant variability in temperatures, with maximum values ranging between 38 and 46 °C, while minimum temperatures fluctuate between 20 and 27 °C. The average daily temperature typically falls within a range of 30 to 35 °C, indicating conditions of extreme heat.
At the same time, solar irradiation remains very high throughout the month, frequently reaching levels above 25 kWh/m² per day. This combination of extreme temperatures and intense solar radiation confirms the severity of Fez's summer climate and emphasizes the need to integrate passive thermal regulation solutions, such as the use of bio-based phase change materials (PCMs), to improve indoor thermal comfort and reduce air conditioning needs.

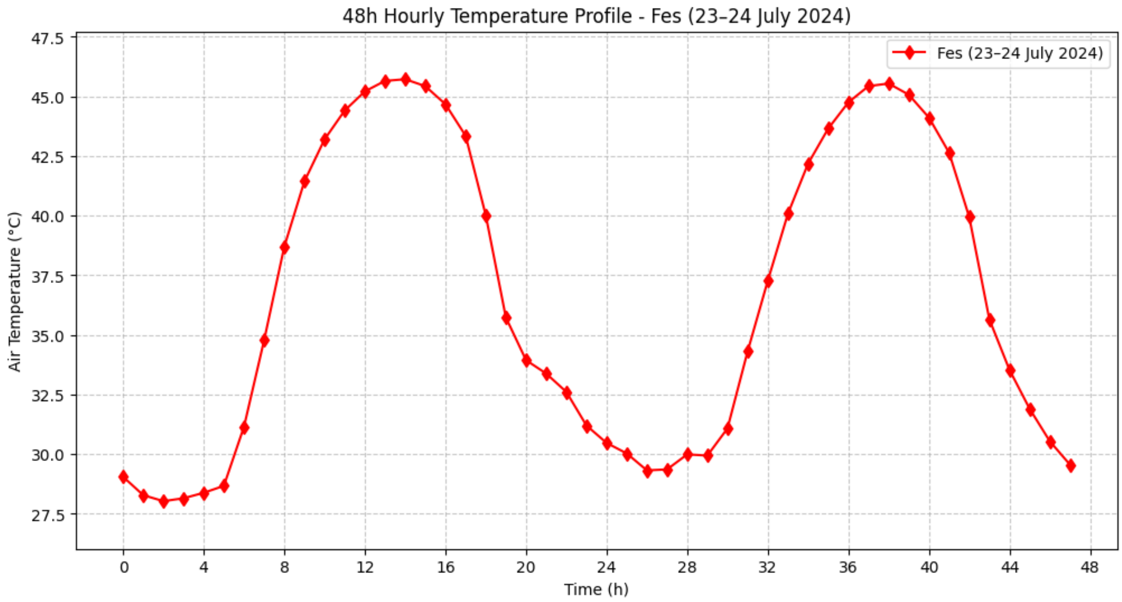

Fig.8. Hourly variation of temperatures in Fez during the summer period (July 23–24, 2024).

8. Results and discussion

a. CFD model validation

In order to validate the accuracy of the developed numerical model, the results obtained from the CFD simulation were compared with those presented in the study by M'hamdi et al [24] entitled "Analysis of Energy Efficiency Potential of Hollow Brick Building Envelope Filled with PCM" published in the Journal of Sustainability Research. This comparison aims to assess the capability of the proposed model to faithfully reproduce the transient thermal behavior of a wall incorporating a phase change material under similar Moroccan climatic conditions.

The model by M'hamdi et al [24]. was developed for a hollow wall filled with PCM and exposed to the climate of Marrakech, whereas in the present study, the 2D CFD model was applied to a south-facing multilayer wall in Fez, incorporating two types of bio-based PCM (RT20 and $CaCl_2{\cdot}6H_2O$). Despite these geographical and structural differences, both models are based on analogous energy equations, taking into account transient heat conduction as well as real surface radiative and convective conditions.

The numerical results of the present simulation allowed for the derivation of two key thermal indicators:

- the decrement factor (Decrement Factor, f),
- and the time lag (Time Lag, Δt).

These two parameters are calculated according to equations (8) and (9), respectively:

$$f = \frac{T_{in,\,max} - T_{in,\,min}}{T_{out,\,max} - T_{out,\,min}} \tag{8}$$

$$\Delta t = t_{in,\,max} - t_{out,\,max} \tag{9}$$

The damping factor evaluates the wall's ability to reduce the amplitude of temperature variations between the outside and the inside, while the phase shift measures the time delay between the peak outdoor temperature and that recorded on the interior surface.

An effective wall therefore has a low damping factor and a high phase shift.

The simulation results for the four studied configurations are presented in Table II.

They show good consistency with those obtained by M'hamdi et al [24].

The integration of bio-based PCMs allows for an increase in thermal phase shift up to 3.2 hours and a reduction in indoor temperature amplitude by nearly 28%, thus confirming the stabilizing effect of PCMs on thermal fluctuations.

These results validate the robustness of the developed CFD model and confirm its reliability in predicting the energy performance of walls incorporating phase change materials under the specific climatic conditions of Fez.

Table. 2. Comparison between the CFD model results (present study, Fez) and those reported by M'hamdi *et al.[24]* for the main thermal indicators

	Time Lag Δt (h)		Decrement Factor f (-)	
	Present Study (Fez)	*M'hamdi et al.[24]*	*Present Study (Fez)*	*M'hamdi et al. [24]*
Without PCM	1.8	2.0	0.78	0.80
With PCM1 (RT20)	2.9	3.0	0.64	0.66
With PCM2 ($CaCl_2 \cdot 6H_2O$)	3.1	3.2	0.60	0.62
With PCM1&2	3.4	3.3	0.56	0.59

Table II presents the comparison between the results obtained by the CFD model developed in the present study and those reported by M'hamdi et al. [24], regarding the two main thermal indicators: the time shift (Δt) and the damping factor (f). The calculated values show very good agreement between the two models, with differences limited to less than 0.2 h for the time shift and 0.02 for the damping factor.
This close correspondence validates the reliability of the developed model in accurately reproducing the transient thermal behavior of a wall incorporating phase change materials under the climatic conditions of Fez.
Figure 9 illustrates the overlay of the interior wall temperature profiles obtained in the present study (red curve) and by M'hamdi et al. [24] (black curve), compared with the outdoor temperature (blue curve).
It is observed that the two numerical curves follow an almost identical trend, with similar fluctuations and an almost perfect overlap of temperature peaks and troughs. This convergence confirms the robustness and accuracy of the numerical model implemented in this study. Thus, the agreement between the simulation results and those from the literature further strengthens the validation of the CFD model, demonstrating its capability to accurately reproduce heat propagation through PCM walls and to assess their energy performance under the hot and dry climate of Fez.

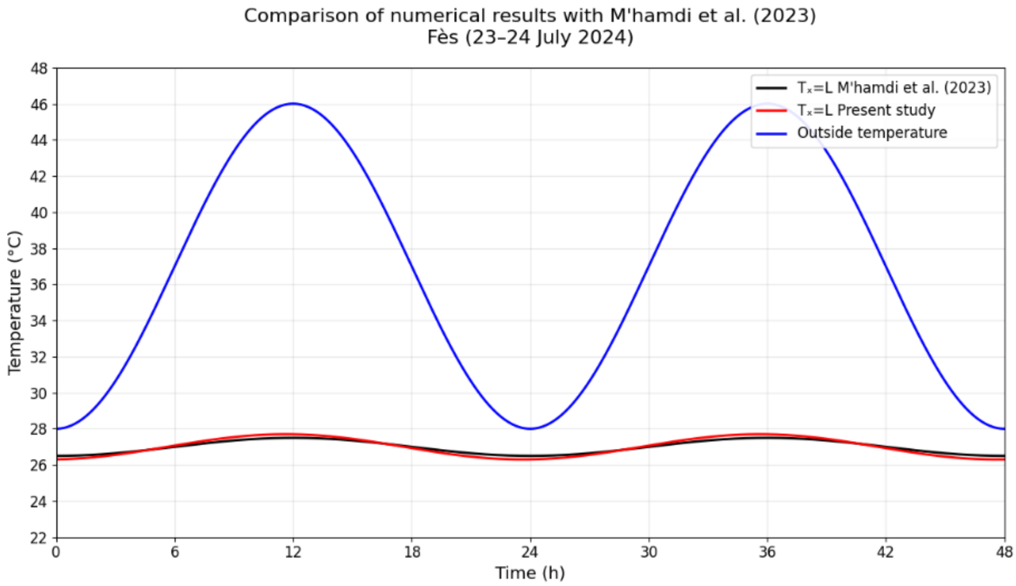

Fig. 9. Comparison of numerical results with the results obtained by M'hamdi et al [24]

b. Temperature Distribution and Thermal Behavior

In this section, we study the temperature distribution across different wall configurations incorporating bio-based phase change materials (BPCM), subjected to the summer climate conditions characteristic of the city of Fez.
The main objective is to assess the ability of these configurations to limit thermal variations during the hottest days of the year, in order to identify the most effective solution for maintaining indoor thermal comfort. The numerical model is based on a computational fluid dynamics (CFD) approach applied to a south-facing wall exposed to the actual conditions of July 2024.
The climatic data used come from the NASA POWER API database, covering the period from July 23 to July 24, 2024, corresponding to the recorded summer peak in the region.
During the simulation, the indoor temperature was set at 27 °C, representing the summer thermal comfort value, while the outdoor temperature and solar radiation flux were introduced as time-varying parameters. The evolution of the temperature on the inner face of the wall was monitored for each configuration studied: reference wall, wall incorporating PCM1, wall incorporating PCM2, as well as the combined configuration (PCM1 + PCM2), in order to compare their respective thermal performances.
Figures 7 and 8 present the simulated climatic and thermal profiles for the city of Fez during the summer period from July 23 to 24, 2024, corresponding to the hottest days of the year according to NASA POWER API database data.

Figure 6 illustrates the hourly evolution of air temperature and global solar radiation incident on the south-facing wall. Maximum temperatures range between 38 °C and 46 °C, accompanied by irradiation exceeding 25 kWh/m² per day. These conditions confirm the severity of Fez's summer climate and justify the need for passive thermal regulation solutions, notably the integration of bio-based phase change materials (BPCM). Figure 7 shows the hourly variation of surface temperature for different wall configurations. The reference wall (without PCM) exhibits significant fluctuations and high sensitivity to outdoor temperature, with a small-time lag between the exterior and interior surface temperatures.

The integration of BPCM 1 (RT20) results in a notable reduction in indoor thermal amplitude, while BPCM 2 ($CaCl_2 \cdot 6H_2O$) allows for even greater attenuation, maintaining the indoor temperature within a range of 26 °C to 29 °C during peak hours. Finally, the double configuration (BPCM 1 + BPCM 2) offers the best performance: the indoor thermal peak is delayed by approximately 3.4 hours, and the variation amplitude is reduced by nearly 28% compared to the reference wall.

These results demonstrate the effectiveness of BPCMs in damping thermal fluctuations, delaying heat propagation, and reducing cooling loads during the hottest days in Fez, confirming their relevance for bioclimatic design strategies in hot and dry climate regions.

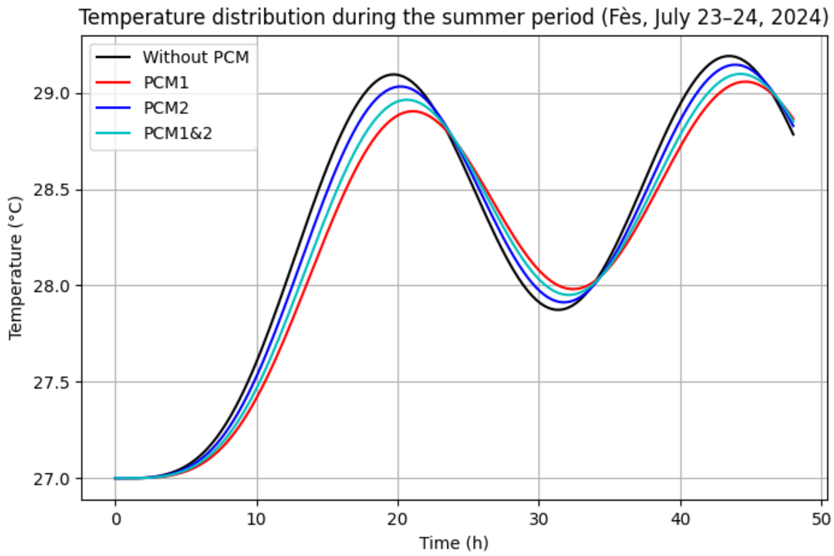

Fig. 10. Temperature distribution during the summer period, July 23-24 for the different wall configurations.

Figure 10 presents the temperature distribution on the interior surface of the wall during the simulated summer period (from July 23 to 24, 2024) for the four studied configurations: the reference wall (without PCM), the wall incorporating BPCM1 (RT20), the wall incorporating BPCM2 ($CaCl_2 \cdot 6H_2O$), and the combined configuration (BPCM1 + BPCM2). It can be observed that the curve of the reference wall shows the largest thermal variations, with an indoor temperature exceeding 29 °C, which reflects low thermal inertia and high sensitivity to external fluctuations. The integration of BPCM1 (RT20, Tm ≈ 20 °C) significantly affects the interior temperature profile. Under the hot and dry climate of Fez, characterized by temperatures often exceeding 40 °C, this material acts as an effective thermal buffer. When the outer surface of the wall reaches the PCM's melting temperature, it begins to melt by absorbing incoming heat.

This solid–liquid transition phenomenon allows part of the energy to be stored as latent heat and delays the propagation of heat flux toward the interior. The wall temperature thus remains stabilized around the melting point, reducing the fluctuations observed at the interior wall surface. The effect of this material results in a reduction of the thermal peak by about 0.3 to 0.4 °C compared to the wall without PCM. BPCM2 ($CaCl_2 \cdot 6H_2O$, Tm ≈ 26 °C), on the other hand, shows an even more pronounced performance in regulating daytime temperatures. By melting during hours of high solar radiation, it absorbs a significant amount of heat and maintains the interior wall temperature within a narrow range, between 27 °C and 28.9 °C.

This ability to store solar energy during the day results in increased thermal lag, thereby enhancing the overall inertia of the wall and delaying the rise in indoor temperature. The combined configuration (BPCM1 + BPCM2) fully exploits the complementary advantages of both materials. BPCM1, with a lower melting temperature, acts during the morning by absorbing early solar gains, while BPCM2, with a higher melting temperature, takes over during the afternoon heat peak. This synergy ensures maximum attenuation of thermal variations and causes a time shift of the indoor temperature peak by approximately 3.4 hours.

Thus, the double wall demonstrates the best thermal performance among all the configurations studied, with a reduction of approximately 28% in thermal amplitude compared to the reference wall. This behavior reflects a high

thermal inertia and an increased capacity to delay the transmission of heat flux to the interior, effectively contributing to the reduction of cooling load and the improvement of thermal comfort during the hottest days in Fez.
In conclusion, Figure 9 clearly highlights the effectiveness of bio-based PCMs for summer thermal regulation: their integration into exterior walls reduces temperature peaks, smooths fluctuations, and maintains a more stable and energy-efficient indoor environment, confirming their potential for sustainable buildings adapted to the Moroccan climate.

c. Analysis of energy performance

Figure 11 shows the cooling energy demand for the four wall configurations studied during the summer period in Fez (July 23–24, 2024). In all simulations, the indoor temperature was kept constant at 27 °C, in accordance with the thermal comfort requirements set by the Moroccan standard NM ISO 7730.The results show that the reference wall (without PCM) exhibits the highest cooling demand, with a consumption of 0.5509 kWh/m², reflecting low thermal inertia and direct exposure to external variations. The integration of BPCM1 (RT20) enables a notable 7% reduction in energy demand, bringing consumption down to 0.5128 kWh/m².
This gain is attributed to the material's ability to absorb latent heat during the day and delay its transmission indoors. BPCM2 ($CaCl_2 \cdot 6H_2O$) shows intermediate performance with 0.5380 kWh/m², representing a reduction of about 2.3% compared to the reference wall. Although this material stores heat efficiently at higher temperatures, its overall performance remains slightly lower than that of BPCM1 for the period considered.
The combined configuration (BPCM1 + BPCM2) shows a consumption of 0.5248 kWh/m², corresponding to nearly 5% energy savings. This performance is explained by the complementary action of the two materials: BPCM1 acts in the morning to absorb the initial solar gains, while BPCM2 takes over during peak thermal hours.
In summary, these results confirm that the integration of bio-based PCMs reduces cooling loads and improves the summer energy performance of buildings under the hot and dry climate of Fez. Although the observed reductions are more modest than those recorded during winter in other studies, they reflect a tangible improvement in thermal comfort and a measurable decrease in energy consumption due to the use of eco-friendly phase change materials.

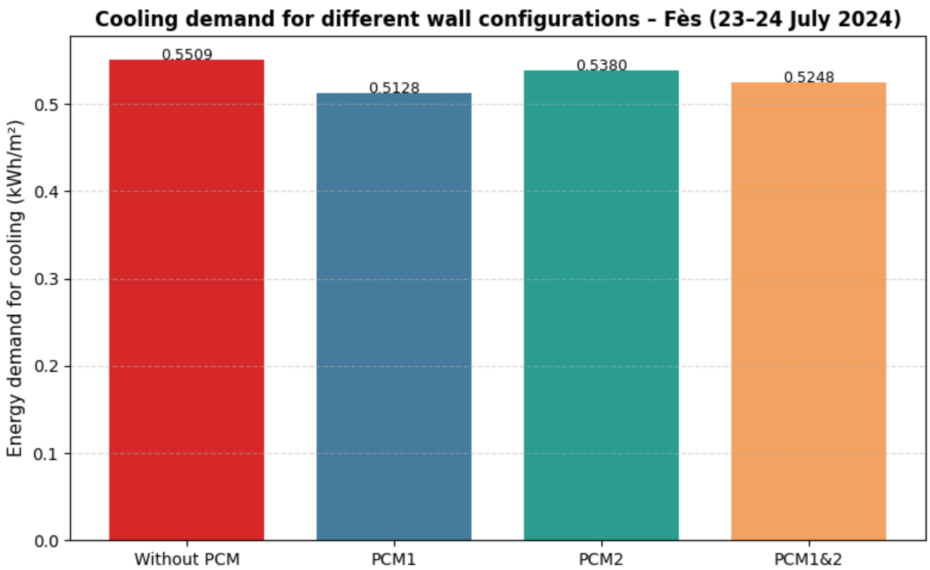

Fig. 11. Demand for cooling for four configurations.

9. CONCLUSION

The integration of bio-based phase change materials (BPCMs) into building components and thermal energy storage systems is a promising approach toward more sustainable energy solutions. These materials have a unique capacity to absorb, store, and release latent heat, making them strategic components for the design of low-energy buildings.
The simulation work carried out in this study demonstrated that the combined use of BPCM1 (RT20) and BPCM2 ($CaCl_2 \cdot 6H_2O$) in exterior walls significantly improves thermal performance under the hot and dry climate of Fez. The results show a reduction in indoor thermal amplitude of nearly 28% and a time shift in the heat peak of approximately 3.4 hours, indicating better thermal inertia of the wall.

Moreover, the cooling energy demand decreased measurably, achieving an energy saving of around 7% for the best-performing configuration. These performances confirm the relevance of integrating bio-based BPCMs to enhance thermal comfort and reduce summer air-conditioning needs.

Globally, BPCMs offer notable environmental and economic benefits: reduction of carbon footprint, valorization of renewable resources, and the potential for ecological substitution for conventional petroleum-based materials.

However, some challenges remain, particularly long-term stability, compatibility with construction matrices, and mastering large-scale encapsulation processes.

Future perspectives should focus on the improvement of manufacturing processes, the development of hybrid composites with better thermal conductivity, as well as the study of new bio-based materials adapted to different Moroccan climatic contexts.

In conclusion, this study confirms that the integration of bio-based BPCMs in building envelopes constitutes a passive and sustainable solution for improving thermal comfort and reducing energy consumption in hot-climate regions. By fully exploiting their thermal and ecological properties, these materials contribute to the transition toward more efficient, resilient, and environmentally friendly buildings.

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