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Article

Assessing the effectiveness of bioclimatic strategies in improving thermal comfort and reducing energy consumption in a house located in a desert climate

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Abstract: This article examined the effectiveness of bioclimatic strategies to enhance thermal comfort and decrease energy consumption in a desert-climate residence. The study assessed the impact of thermal insulation, natural ventilation, and phase-change materials (PCMs) over a year, with each strategy evaluated both independently and in combination. Monthly energy bills were analyzed to determine the impact of these strategies. The results indicated substantial reductions in energy costs, with decreases of up to 50% during transitional seasons; however, the complete elimination of heating and cooling systems was not feasible due to significant thermal phase differences between indoor and outdoor environments. Further analysis of thermal discomfort hours revealed that increasing insulation thickness during specific seasons could mitigate peak heat intensity and delay its occurrence, thus extending periods of comfort and reducing discomfort hours. Despite these improvements, some periods of thermal distress persisted during the warmest months, underscoring the necessity for a balanced approach to climate adaptation strategies. Overall, the implementation of these strategies proved effective in improving comfort and reducing energy usage in desert-climate homes, although they do not fully negate the need for traditional heating and cooling systems.

Keywords: bioclimatic strategies; thermal comfort; energy consumption; desert climate; thermal insulation; phase-change materials; natural ventilation; energy bills

1. Introduction

During the past decade, the building sector in Algeria has emerged as one of the major consumers of energy, accounting for approximately 40% of total fossil energy consumption [1,2]. According to the annual statistics on energy consumption in residential buildings provided by the National Energy Balance Sheet of Algeria's Ministry of Energy, the residential sector in Algeria has witnessed a steady increase, with a share of 40% in 2010, 43% in 2013, and 46.7% in 2020 [1]. Additionally, Algeria is particularly vulnerable to extreme heat, with the Algerian desert experiencing record-breaking temperatures, especially in southern regions, such as Illizi, Ouargla, Adrar, and Ghardaïa, where temperatures reached 51 °C in July 2021 [1]. This exceptional situation has resulted in a substantial increase in energy consumption, imposing a heavy burden on the economy. Moreover, there have been challenges in implementing regulations and decisions related to energy conservation

[2]. As a result, current policies are focused on improving building energy performance and promoting the use of renewable energy sources.

An effective strategy for enhancing energy efficiency in the construction sector is to prioritize the design and construction of the building envelope. A building envelope, including walls, roofs, windows, and doors, serves as a barrier between the interior and exterior environments and plays a crucial role in controlling energy loss or gain [3–5]. By optimizing the design of a building envelope, it is possible to minimize unwanted heat transfer through conduction, convection, and radiation. This can be achieved through various means, such as using high-quality insulation materials, incorporating thermal breaks, sealing air leaks, and choosing appropriate glazing systems for windows.

Additionally, the orientation of a building and the placement of windows can significantly impact energy efficiency. By taking advantage of natural light and solar heat gain during colder periods, the need for artificial lighting and heating can be reduced. On the other hand, during hot periods, proper shading and window design can minimize solar heat gain and reduce the reliance on mechanical cooling systems.

Furthermore, there are periods when a building remains unoccupied or has reduced occupancy, such as during nights, weekends, or holidays. During these periods, it is important to implement strategies to optimize energy consumption. This can include adjusting temperature setpoints, implementing setback or shutdown modes for HVAC systems, and utilizing energy management systems to monitor and control energy usage.

Overall, giving priority to the building envelope and considering periods of reduced occupancy are effective strategies for enhancing energy efficiency in the construction sector. By focusing on the design, insulation, orientation, and control of the building envelope, significant energy savings can be achieved, leading to reduced operational costs and a more sustainable built environment [6–9].

Active and passive energy-saving strategies to reduce building energy consumption, while sustaining internal thermal comfort, have been extensively studied by scholars [5–7]. Active technologies frequently encounter obstacles relating to low energy efficiency [8], resulting in a growing interest in passive energy-efficient technologies [9]. Incorporating Trombe walls [10,11], lightweight concrete walls [12], insulation materials [13], retro-reflective materials [11], green roofs [10], and phase-change materials (PCMs) [14,15] are examples of passive strategies. PCMs are particularly important for energy storage, offering benefits such as free cooling and enhanced thermal comfort, especially in hot climates, with minimal energy use. This contributes significantly to mitigating the global warming crisis. Passive technologies have proved effective in reducing peak loads, supported by both experimental and numerical studies [16–18]. To this end, PCMs are usually integrated into external building walls. In a recent study, Zhou and Razaqpur [19] developed a new dynamic Trombe wall that combined insulation and a PCM in order to improve thermal efficiency. They compared the thermal performance of this wall with that of static walls using a large-scale model and computational fluid dynamics (CFD), showing up to 25.3% greater energy-saving efficiencies and up to 79.8% higher thermal efficiencies. Their results suggested better thermal performance, with higher temperatures in the conditioned space of the proposed wall during PCM discharging periods. Anter et al. [20] produced significant findings in their study, which investigated how building walls integrated with different types and thicknesses of PCMs behaved thermally over an extended period of time in Egypt's environment. Through the use of two-dimensional CFD simulations, they evaluated the types and locations of PCMs. The findings showed that the addition of PCMs successfully lowered indoor heat flux, bringing interior wall temperatures into compliance with target ranges. The PCM of RT-35HC demonstrated exceptional thermal performance, especially when positioned 1.5 cm from the inner and outer walls. Muzhanje and Hassan's [21] study focused on optimizing PCMs in a variety of encapsulation geometries. They investigate diverse PCMs by merging them with distinct nanoparticles through thermal investigation and modeling. They emphasized free heating in cold locations and concentrated on improving heat transfer, especially for structures. The results showed that rectangular capsules melted and solidified up to 41% faster [22–24].

A cooling system using PCMs and heat exchangers shows promise for energy-efficient cooling and ventilation in hot climates. The system reduces supply air temperature by 2 °C with minimal energy consumption, improving indoor air quality and extending thermal comfort.

This article examined the effectiveness of bioclimatic strategies in enhancing thermal comfort and decreasing energy consumption in a desert-climate residence. The study assessed thermal insulation, natural ventilation, and PCMs over a year, with each strategy evaluated both independently and in combination.

2. Methodology

The building used in this study is a functional house designed using Google SketchUp located at the Applied Research Unit in Renewable Energies (Unité de Recherche Appliquée en Energies Renouvelables, or URAER) in Ghardaïa, Algeria. Climate measurements were sourced from a radiometric station situated on the roof of the URAER building. The building geometry was exported in the IDF format from Google SketchUp and subsequently imported into modeling software TRNBUILD TRNSYS 18. Meteorological data were incorporated into Simulation Studio software using Type 109, and initial simulations were conducted without strategic interventions, relying solely on the inherent properties of building components, such as walls, ceilings, and windows.

Following the analysis of the initial results, strategic solutions were implemented, beginning with the introduction of phase-change materials, followed by the integration of insulating panels and improvements to ventilation systems based on established references. For a detailed depiction of the simulation process, refer to **Figure 1** in the simulation flowchart.

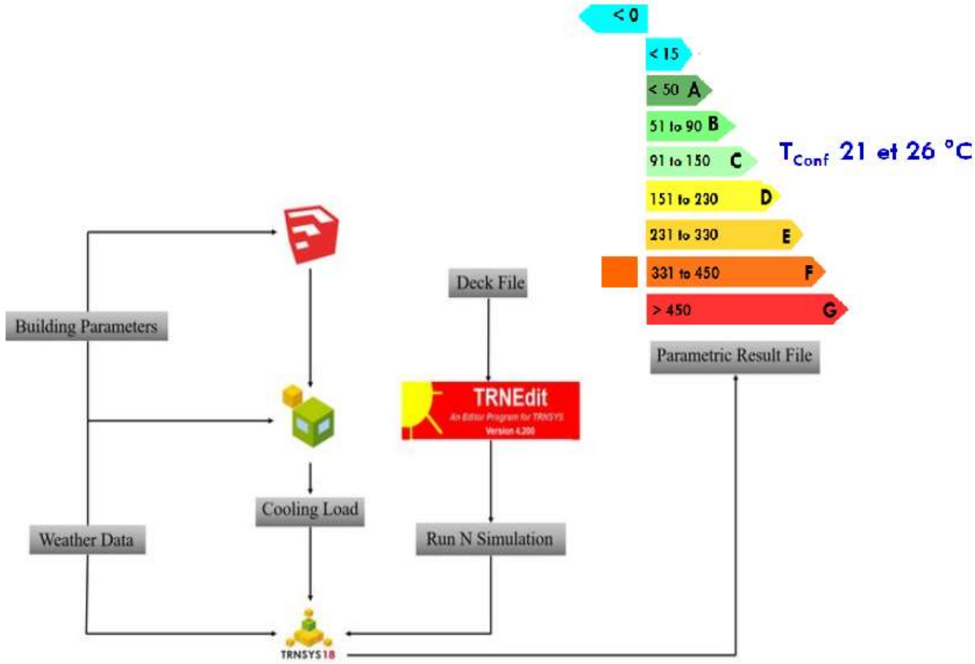

Figure 1. Simulation flowchart.

To evaluate the effectiveness of bioclimatic strategies aimed at enhancing thermal comfort and reducing energy consumption in a desert-climate residence, this study undertook a comprehensive year-long assessment. The strategies examined included thermal insulation, natural ventilation, and the utilization of PCMs. Each strategy was evaluated both independently and in combination to assess their individual and collective impacts.

3. Influence of weather conditions on thermal comfort in Ghardaïa

Ghardaïa, located in the heart of the Northern Sahara, experiences a typical desert climate characterized by extremes in temperature and low humidity levels. The region sees an average annual temperature of 22.61 °C, with winter lows dropping to 5.5 °C in January and summer highs peaking at 41.7 °C in July. Relative humidity remains notably low, averaging 38.33% annually and dropping to 21.60% in July, when temperatures are at their highest. Ghardaïa benefits from abundant sunshine, with an average annual solar radiation exceeding 20 MJ/m^2 and sunshine duration surpassing 3000 h/year. This high insolation rate, coupled with minimal cloud cover, makes it conducive for harnessing solar energy across various applications in the region. The established distribution, as shown in **Figure 2**, is strongly linked to the average cloud cover of the sites.

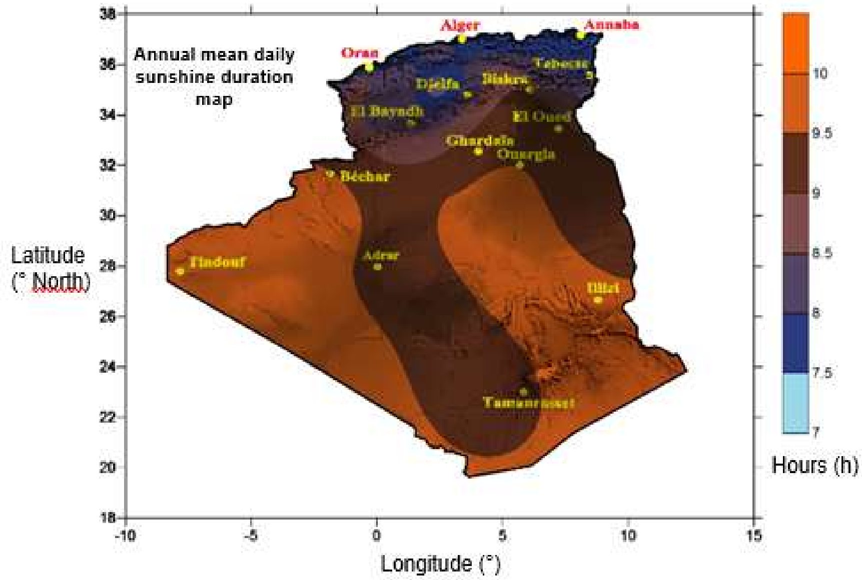

Figure 2. Mapping of average annual values of measured insolation duration (1992–2002) [2].

After conducting a bioclimatic analysis of thermal comfort in our climatic zone in Ghardaïa, we found that the environment was relatively comfortable for approximately 1732 h, or 19% of the total annual time (8760 h) in **Figure 3**. This annual and monthly analysis of thermal comfort provided us with the necessary bioclimatic solutions for developing our architectural project. In other words, we developed an appropriate design method to seamlessly integrate our built project with its climatic environment, while ensuring optimal energy performance and comfort. To achieve this, we proposed passive solutions, which where thermal insulation, natural ventilation, and phase-change materials, to formulate recommendations at various levels.

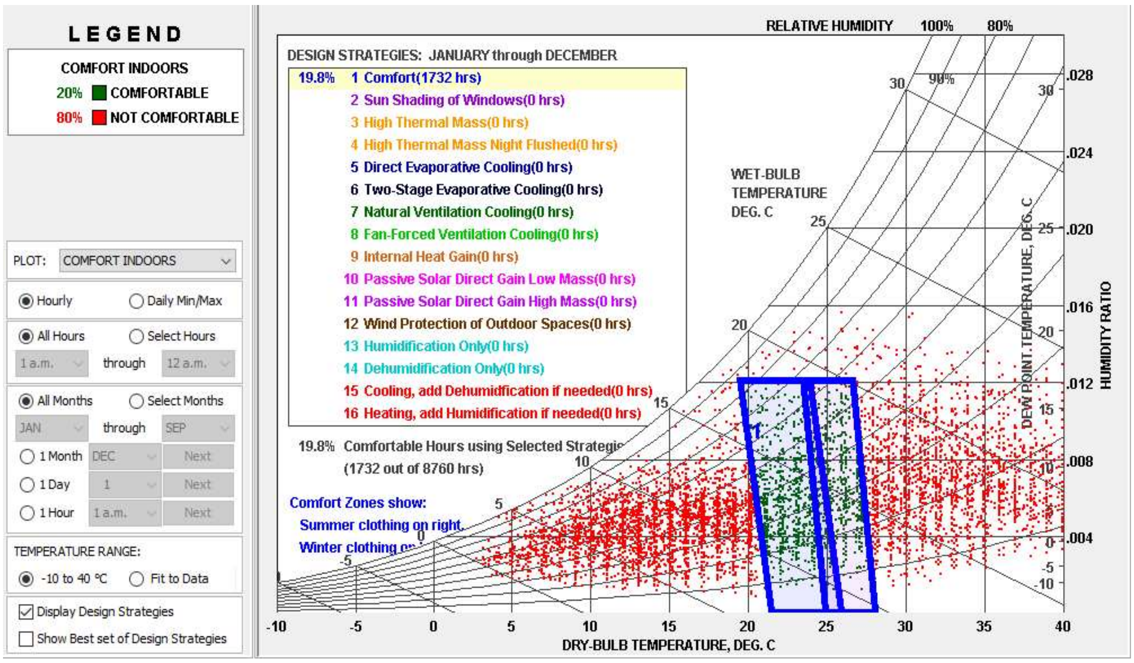

Figure 3. Psychrometric chart of thermal comfort and design strategies for climatic zone in Ghardaïa.

For a more detailed monthly analysis, we calculated the number of hours of comfort and discomfort for each month of the year in Ghardaïa. The figures are depicted in **Figure 4**.

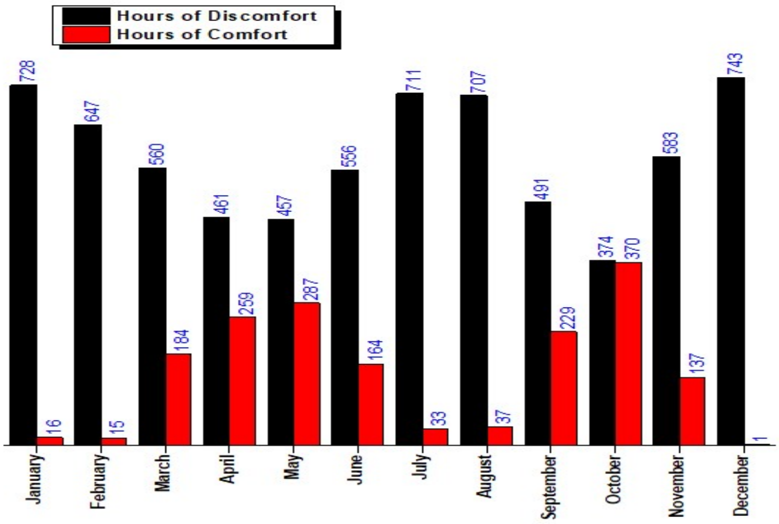

Figure 4. Histogram of hours of comfort and discomfort.

The most comfortable months in terms of thermal comfort in Ghardaïa are March, April, May, September, and October, with comfort hours ranging from 229 to 370 h. These months have a relatively balanced distribution between comfort and discomfort hours, indicating a transition period between the high temperatures of summer and the cooler temperatures of winter. The summer months, especially July and August, are the least comfortable, with very few comfort hours and many discomfort hours. It is important to consider these temperature variations when designing and constructing buildings in this region to ensure optimal thermal comfort for occupants. However, it is important to note that these data do not take into account other factors, such as humidity and wind speed, which can also impact thermal comfort.

According to the provided data, July recorded the highest total number of hours (744 h) and also the highest number of discomfort hours (711 h), with only 33 h classified as comfortable. This is likely due to the intense summer heat that often characterizes this time of year.

January, February, and December all have a total of 744 h but with different levels of discomfort. January has the lowest discomfort level with only 16 comfort hours, while December has the highest discomfort level with only 1 comfort hour. This suggests that December is the most challenging in terms of thermal comfort.

April, May, and September also have high levels of discomfort with over 200 discomfort hours for each month. This may be due to the high temperatures during the day.

March, June, and November have a significant number of comfort hours, indicating that these months are relatively pleasant in terms of thermal comfort.

October and November have a fairly equal distribution between comfort and discomfort hours, suggesting a transitional period between summer heat and winter cold.

4. Passive energy optimization using thermal insulation alone

Insulation plays a crucial role in reducing heating and cooling needs by minimizing heat loss during the winter and limiting heat gain during the summer. By optimizing a building's insulation, it is possible to maintain a more stable indoor temperature and reduce reliance on traditional heating and cooling systems.

In this study, we explored the effectiveness of thermal insulation alone, without using any other active heating or cooling systems and without employing other passive strategies. In the first case, we varied the thickness of the insulation from 1 cm to 10 cm for all interior surfaces, excluding the roof insulation, to evaluate the importance of insulation on vertically exposed surfaces directly affected by radiation. In the second case, we insulated only the roof to compare the results and analyze the energy consumption for each month [13–15].

The application of thermal insulation helps reduce air temperatures, resulting in increased occupant comfort. In this scenario, the addition of thermal insulation led to a 7.3% improvement in comfort, equivalent to an additional 642 h of comfort. This means that occupants were able to experience a thermal comfort sensation during these additional hours.

In this case, occupant comfort reached 27.1%, representing a higher proportion of time spent in thermal comfort conditions. This corresponds to 2374 h of comfort.

Table 1 presents the energy consumption in different insulation cases compared with that of an ordinary case.

Table 1. Energy consumption in different insulation scenarios compared with ordinary case.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
Ordinary case	Heating (kWh)	3570	2210	873	45.8	0	0	0	0	0	65.6	897	3100	10800
	Air conditioning (kWh)	0	0	0	0	10.6	903	2700	4350	3790	1900	244	0	13900
Insulation: 10cm Walls	Heating (kWh)	1700	947	205	0	0	0	0	0	0	0	155	1350	4350
	Air conditioning (kWh)	0	0	0	0	10.6	903	2700	4350	3790	1900	244	0	11400
Insulation: 10cm Walls + 10cm roof	Heating (kWh)	1640	1370	1040	305	0	0	0	0	0	1.89	374	1270	6000
	Air conditioning (kWh)	0	0	0	0	0	104	573	572	199	2.83	0	0	1450

The result highlights the importance of thermal insulation and the use of high-mass materials to improve thermal comfort in buildings. By combining these passive strategies, it was possible to reduce reliance on heating and cooling systems, while providing a comfortable indoor environment for occupants:

- Regarding heating, it was observed that energy consumption varied significantly throughout the year. The coldest months (January, February, and December) showed the highest consumption, while the hottest months (May to September) showed zero consumption. By adding a 10-cm layer of polystyrene insulation to the exterior walls of the building, heating consumption was significantly reduced for all months, reaching zero even for the months from April to October. The addition of thermal insulation resulted in a substantial reduction in heating consumption for all months of the year, especially for the milder months, such as May to September. In fact, for these months, heating consumption reached zero, indicating that the building did not require heating to maintain a comfortable temperature. Thermal insulation also proved effective for the transitional months of April and October, as heating consumption was significantly reduced, although not completely eliminated. This demonstrates that thermal insulation is an effective solution for reducing heating costs and improving the energy efficiency of a building.

- As for cooling, energy consumption was observed to be higher during the summer months (June to August), with zero consumption during other months. The addition of a 10 cm layer of polystyrene insulation to the exterior walls resulted in a significant reduction in cooling consumption during the hottest months. For example, in July, energy consumption decreased from 4350 kWh to 3180 kWh. However, during the months of April and October, thermal insulation posed a challenge, as consumption slightly increased, indicating that it may not be an effective solution during these overlapping transitional periods. It is important to consider local climatic conditions when designing and implementing energy efficiency measures to ensure they are suitable for the specific building situation. In the case of 10 cm of insulation on the exterior walls, there can be significant benefits in terms of energy efficiency and a reduction in heating and cooling costs. However, there is an exception during the transitional periods, where insulation may not be effective and can pose challenges, as the insulation efficiency reduced during the transition periods between interseasons. This can limit the usefulness of insulation during these overlapping seasons. Comparing the three cases, we can see that adding 10 cm of insulation to the exterior walls and roof leads to a significant reduction in energy consumption for heating and cooling compared with the normal case. Specifically, when using 10 cm of insulation to the exterior walls, the total energy consumption for heating is reduced by more than half, from 10800 kWh to 4350 kWh, while the total energy consumption for cooling is reduced by nearly 18%, from 13900 kWh to 11400 kWh. Compared with adding insulation to the exterior walls only, adding insulation to both the exterior walls and roof yielded a better result, especially in terms of cooling, where total energy consumption is reduced by nearly 45% compared with a reduction of only about 18% for adding insulation to the exterior walls. In summary, adding insulation to the exterior walls and roof is the best option for reducing energy consumption for heating and cooling, and it can result in significant long-term energy bill savings (**Figure 5**).

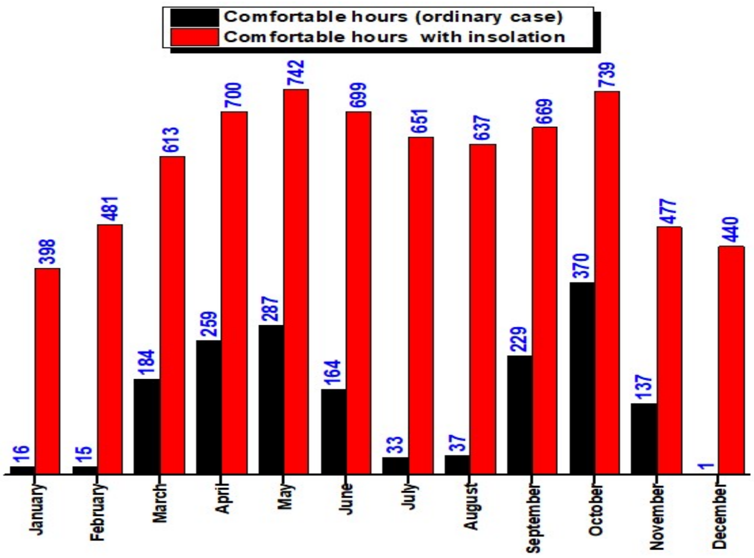

Figure 5. Histogram of comfort hours for thermal insulation case and ordinary case.

We can observe that the coldest months, which are January, February, and December, showed the highest number of hours of thermal discomfort, even with the addition of insulation. These months exhibited high levels of thermal discomfort, even with insulation, indicating that insulation alone is not sufficient to maintain a comfortable temperature during the coldest months. On the other hand, the hottest months, which are May, July, and August, showed the lowest number of hours of thermal discomfort. This suggests that insulation has a positive effect on reducing excessive heat during the summer.

After the data were analyzed, it was evident that the addition of insulation resulted in a reduction in the number of hours of thermal discomfort for most months. However, during the coldest months, there were still hours of thermal discomfort, even with insulation. Therefore, other strategies needed to be considered to enhance the thermal performance of the building during these months, such as the use of high-performance construction materials, such as phase-change materials, as well as natural ventilation for intermediate and summer periods.

5. Passive energy optimization using PCM

In this study, we chose the integration of a PCM to weaken or even eliminate the effects of the thermal load of the envelope shown in **Table 2**. A PCM can also be passively incorporated into ceilings on a permanent basis. In this case, we put a PCM in the inner layer of the ceiling in the form of lightweight, portable sheets that can be removed and replaced whenever needed, in accordance with the study by Hamdani et al. [2]. The objective was to determine the effect of PCMs on the evolution of the internal temperatures of the different zones of the habitat under the climatic demands of an arid climate throughout the year, with priority given to days when the outdoor temperature converged with the melting point of the PCMs. This endeavor aimed to take advantage of PCMs' ability to retain and discharge heat.

Table 2. Monthly and annual energy needs for heating and cooling with PCM layer (kWh).

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
PCM layer	Heating (kWh)	2190	1302	412	39	0	0	0	0	0	162	420	1750	6275
	Air conditioning (kWh)	0	0	0	86	790	1830	2550	2230	950	40	0	0	8476

The simulations were based on a building envelope reinforcement using a layer of a removable PCM via PCM panels on the internal ceiling of the sitting room and comparing the performance with that of the same room without the PCM panels. We then analyzed the monthly energy savings and the average indoor air temperatures of the room by modeling the thermal and energy performance of the building using TRNSYS-18 and Type 285 [2]. Through the result obtained, we made special configurations.

The result indicated a decrease in the percentage of energy consumption in March, April, and May, when the lowest numbers were recorded at 25.7 kWh, 27.8 kWh, and 114 kWh, respectively, without placing a PCM inside the building. The month of June also witnessed the beginning of a rise in consumption. It reached its peak consumption in July with an amount of 480.3 kWh, and it continued to rise in the month of August at 312.2 kWh. In this case, the most suitable solution was to put on the PCM of Rt21 in both June and July, but in the month of August, we replaced the PCM with another type, Rt26, because it was the most suitable. The result showed a remarkable decrease in temperature when comparing the building with and without a PCM. Hence, we found that in some months of the year, the PCM must be removed because it does an undesirable reverse action, which is increasing the demand for energy. Then we put on Rt21 in September, October, November, December, and January because it gave a good result compared with that of Rt26.

6. Conclusion

Thermal insulation and PCMs represent pivotal passive strategies in enhancing thermal comfort and curbing energy consumption within desert-climate residences:

- Varying insulation thickness on interior surfaces and implementing roof-only insulation improved thermal comfort by 7.3%, translating to 642 additional hours of comfort.
- Using 10cm insulation on walls and the roof decreased cooling energy demand by up to 45% during peak summer months.
- Challenges during transitional seasons underscore the need for integrated bioclimatic strategies.
- Lightweight PCM sheets on internal ceilings effectively mitigate thermal load, especially near PCM melting points.
- A PCM reduces heating needs in cooler months, particularly in March, April, and May, and moderates peak cooling demands in summer.
- Adaptive strategies, such as alternating the PCM type (e.g., Rt21 and Rt26), are critical for managing PCM efficacy.

Overall, while thermal insulation and PCM integration prove effective in optimizing thermal performance and energy efficiency in arid climates, continuous monitoring and adaptive management are essential. This approach ensures sustained benefits across seasonal variations, underscoring the importance of holistic bioclimatic solutions for resilient and sustainable residential environments.

Author contributions: Methodology, EK and SAS; software, BA; validation, SMEAB and RD; investigation, ZM; data curation, GM; writing—original draft preparation, MH and MKC; supervision, EK and SAS. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

Nomenclature:
PCMs: Phase-change materials—materials that absorb or release heat during phase transitions, used for thermal energy storage in various applications.
Rt21 PCM types: Phase-change materials with a melting point around 21 °C, used for moderate temperature thermal energy storage.
Rt26 PCM types: Phase-change materials with a melting point around 26 °C, suitable for slightly higher temperature thermal energy storage.
TRNSYS-18: Transient System Simulation Tool version 18—a software used to simulate and analyze the transient behavior of thermal systems.
Type285 for PCM in TRNSYS 18: A specific component model in TRNSYS 18 used to simulate the thermal behavior of phase-change materials (PCMs) within a system.

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