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Energy efficiency and hygrothermal performance of hemp clay walls for Moroccan residential buildings: An integrated lab-scale, in-situ and simulation-based assessment

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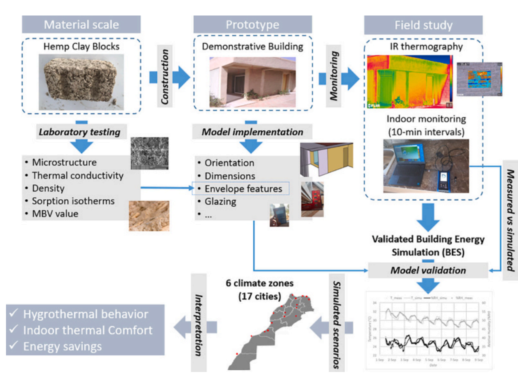
HIGHLIGHTS

- Experimental characterization of thermal conductivity, sorption isotherm, and moisture buffering capacity of hemp bricks.
- Assessment of indoor thermal comfort and energy demand in a hemp-based building across 17 cities in Morocco.
- Hemp-clay bricks demonstrated excellent humidity regulation with a moisture buffer capacity of 2.25 g/m^2%RH.
- Hemp-clay walls can achieve energy savings ranging from 27.7%–47.5% for cooling and 33.7%–79.8% for heating in Morocco.

GRAPHICAL ABSTRACT



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ABSTRACT

Hemp-based building envelopes have gained significant popularity in developed countries, and now the trend of constructing houses with hemp-clay blocks is spreading to developing countries like Morocco. Investigating the hygrothermal behavior of such structures under actual climate conditions is essential for advancing and promoting this sustainable practice. This paper presents an in-depth experimental characterization of a commercial hemp-clay brick that has been exposed to the outdoor environment for four years, in addition to field measurements on a building scale demonstration prototype. Additionally, the study simulates 17 representative cities

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to assess the hygrothermal performance and energy-saving potential in each of Morocco's six existing climate zones, using the EnergyPlus engine. The experimental campaign's findings demonstrate excellent indoor air temperature and relative humidity regulation within the hemp-clay wall building, leading to satisfactory levels of thermal comfort within hemp-clay wall buildings. This is attributed to the material's good thermal conductivity and excellent moisture buffering capacity (found to be 0.31 W/mK and 2.25 g/m^2%RH), respectively). The energy simulation findings also point to significant energy savings, with cooling and heating energy reductions ranging from 27.7% to 47.5% and 33.7% to 79.8%, respectively, as compared to traditional Moroccan buildings.

Nomenclature

HVAC	Heating Ventilation Air Conditioning
LCCA	Life Cycle Cost Analysis
HFM	Heat Flux Meter
MBV	Moisture Buffer Value
BEM	Building Energy Model
BES	Building Energy Simulation
RTCM	Moroccan Thermal Regulation of Constructions
SHGC	Solar Heat Gain Coefficient
ACH	Air Change per Hour
VLT	Visible Light Transmission
BR	Bedroom
LR	Living Room
PMV	Predicted Mean Vote
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
COP	Coefficient Of Performance
EER	Energy Efficiency Ratio
CV(RMSE)	Coefficient of Variation of Root Mean Square Error
NMBE	Normalized Mean Biased Error
SEM	Scanning Electron Microscope

1. Introduction

Nearly one-third of the world's energy is consumed by the building sector, which also emits 40% of all CO_2 emissions [1–6]. Heating, ventilation, and air-conditioning (HVAC) systems account for 50% of the total energy used in residential buildings [7–10]. To reduce the quantity of heating and cooling requirements, modern, highly efficient building techniques like zero-energy and passive buildings emerge, either by adapting the building envelope by adding more insulation or by installing advanced equipment like HVAC and PV systems that consume less energy. Hence, building envelope in residential structures is regarded as one of the most important factors affecting indoor hygrothermal comfort, energy use, and carbon emissions [11]. Therefore, the building envelope should be well-designed and reinforced with good insulation materials to avoid overheating and heat losses. Thus, the literature provides a diversity of energy-efficient building construction and insulation materials [12–18]. Among these bio-sourced materials, hemp composite has recently gained much attention due to its hygrothermal properties. Hemp clay is an eco-friendly building material that is made from fibers, shives, or hurds of the hemp plant, along with lime and water [19]. It is known to be a lot lighter, easier to use, and more durable than conventional concrete material. Furthermore, hemp clay is also incredibly energy-efficient, as it is great at retaining and releasing heat, making it perfect for building insulation [20]. In addition to being cheaper and faster to build, hemp clay blocks are also incredibly strong and durable. They are resistant to fire, moisture, and insects with excellent insulating properties [21]. This makes them ideal for creating safe, comfortable, and energy-efficient constructions. Moreover, hemp clay blocks are also great for the environment, since they are made from natural materials with low energy use in production. They can also be recycled and reused, making them even more eco-friendly [22]. According to the International Narcotics Control Board (INCB), Morocco is considered as the biggest manufacturer of cannabis resin in the world. Moreover, despite all the mentioned pros of the hemp material, and even if Morocco is considered among the first producers and exporters of cannabis waist, the use of hemp fibers is still not spread in the building sector research and industries. Thus, in Morocco only a few studies have been published in the last six years dealing with hemp-based materials [23–28]. For instance, Dlimi et al. [23] have studied the thermal performance as well as the heating and cooling energy use of two types of hemp material, the hemp concrete and the hemp wool, compared to conventional polystyrene insulation. The findings have proved the effectiveness and efficiency of the hemp wool insulation material under the Mediterranean climate of Meknes City in Morocco. Brümmer et al. [24] have investigated the mechanical properties of hemp clay material in order to evaluate its efficiency and practicability compared to the commercial hemp. Moreover, Dlimi et al. [25] have conducted another study in 2019 in order to evaluate the dynamic thermal performance, energy savings and payback period of the optimal hemp wool insulation thickness based on a Life Cycle Cost Analysis (LCCA) carried out for 20 years. Whereas, Charai et al. [26] have evaluated the possible application of a non-industrial hemp in the production of regional bio-insulating plasterboards. Furthermore, Essaghouri et al. [27] have focused on studying the life cycle assessment of using Moroccan hemp biomass in a residential building located in Marrakech City in Morocco. Whereas, Chihab et al. [28] have conducted a characterization and computational analysis in order to prove that by strengthening the material's dynamic thermal properties, hemp fibers may be added to earth bricks to give a sufficient level of thermal comfort.

Furthermore, most of the already conducted studies dealing with hemp material are focusing on material characterization and laboratory testing [29–33], including the measurements of thermal diffusivity and conductivity, the composite microstructure, the absorption and desorption isotherms, the water vapor permeability, the moisture buffer value, the moisture penetration depth as well as the proceeding of carbonation. Whereas, only few studies present in the literature deal with the hemp-based building scale using simulation tools [34–36].

Hence, Morocco. Hence, the motivation and the rationale of this paper were inspired by the mentioned limitations of the studies present in the literature. Thus, the key objective of this paper is to evaluate the impact of using hemp-based building material on the indoor environment performance, indoor occupant thermal comfort, cooling and heating energy consumption, as well as energy savings across all the different climates existing in Morocco. As a result, the main contribution of this study remains in enlarging the literature with new knowledge as well as a detailed methodology on the use of hemp clay blocks from the material scale, using laboratory testing to define the properties of the material, until the building scale using a real existing built construction from hemp clay to evaluate the material energy efficiency. Hence, in order to fill in the major gaps found in the literature; the novelty of this study remains in addressing the following:

- Detailed characterization of hemp clay blocks for building construction using the most crucial laboratory testing.

- Detailed building field measurements and monitoring. The studied building is the first construction built with hemp clay material in Morocco. Lack of real existing hemp-based buildings in literature.
- Detailed hemp-based building energy efficiency and thermal comfort assessment in 6 climatic zones of Morocco. Lack of studies that deal with indoor building material performance, indoor thermal comfort, and energy use aspects altogether for hemp-based construction, especially in all existing climates of Morocco.

The rest of this paper is structured as follows; **Section 2** presents an overview on the research methodology developed under the framework of this study. Then, **Section 3** defines the main materials and methods conducted, including the material description and characterization, field measurement as well as the simulation study. Furthermore, **Section 4** describes and discusses the main results obtained from the followed methodology. Finally, the last **Section 5** gives an overview of the main conclusions and recommendations drawn from the conducted study.

2. Research methodology overview

The overall methodology developed under the framework of this study is summarized in Fig. 1. This study is divided into two main parts, the first deals with the hemp material scale including its characterization and material properties specifications. Whereas, the second part of this paper focuses on the hemp-based building scale with a detailed evaluation of the building material performance, the building's indoor thermal comfort, and energy use performance assessments. Therefore, this study's first part aim is to provide detailed experimental characterizations on the hemp clay block material, including the thermal and hygric properties using the HFM and MBV tests. Then, the second part of the study aims at developing a numerical BEM of the existing real hemp clay building that will be validated and calibrated using 10-min indoor air temperature and relative humidity measured and simulated data. Hence, the numerical model will be simulated in 17 cities all over Morocco in different regions and climate types to assess the energy efficiency of using hemp clay blocks as building construction material compared with a conventional reference Moroccan building mainly built from mortar and concrete construction materials.

3. Materials & methods

3.1. Clay hemp-based blocks

The building material used to build up the studied building was commercial (~0.87 €/unit [37]), air-dried and compressed hemp-clay bricks with dimensions of 30 × 14 × 10 cm^3 and a unit mass of 5.35 kg. This block was manufactured from clay, stabilized with lime, and bio-sourced with industrial hemp fibers. The use of local clay, manual compaction, and the inclusion of hemp fibers led the produced blocks to be an environmentally friendly building material with a negative carbon footprint, as indicated by a Global Warming Potential (GWP) of −0.624 kg CO_2eq/kg [38].

According to the manufacturer [38], the blocks were manually produced using a press and possess physical properties that comply with Spanish standards (e.g., UNE EN). The building material characteristics include an apparent density of 1171 kg/m^3, a mechanical strength of 1.4 MPa (28 days), a thermal conductivity of 0.19 W/mK, and a specific heat capacity of 1113 J/kgK.

Given that the investigated demonstration building in this research was constructed in 2019, it is plausible that the engineering properties of the external construction material may have experienced changes over time due to unstable and harmful outdoor climate conditions. To ensure more accurate interpretations of field measurement findings, it is worth investigating the thermophysical properties of the utilized building material in its present state. Notably, the building materials under question have remained exposed to outdoor climatic conditions without any protective measures since 2019. The tests were conducted on three samples without any prior treatment. In addition, since this study focused on evaluating the hygrothermal performance of clay hemp-based building envelopes, the moisture-related properties of the building material were also identified through experimental testing (Fig. 2). Temperature-dependent thermal conductivity was measured using the 436 Lambda Netzsch heat flow meter (HFM) equipment (Fig. 2 a). Before being tested, the as-received samples were cut to obtain regular

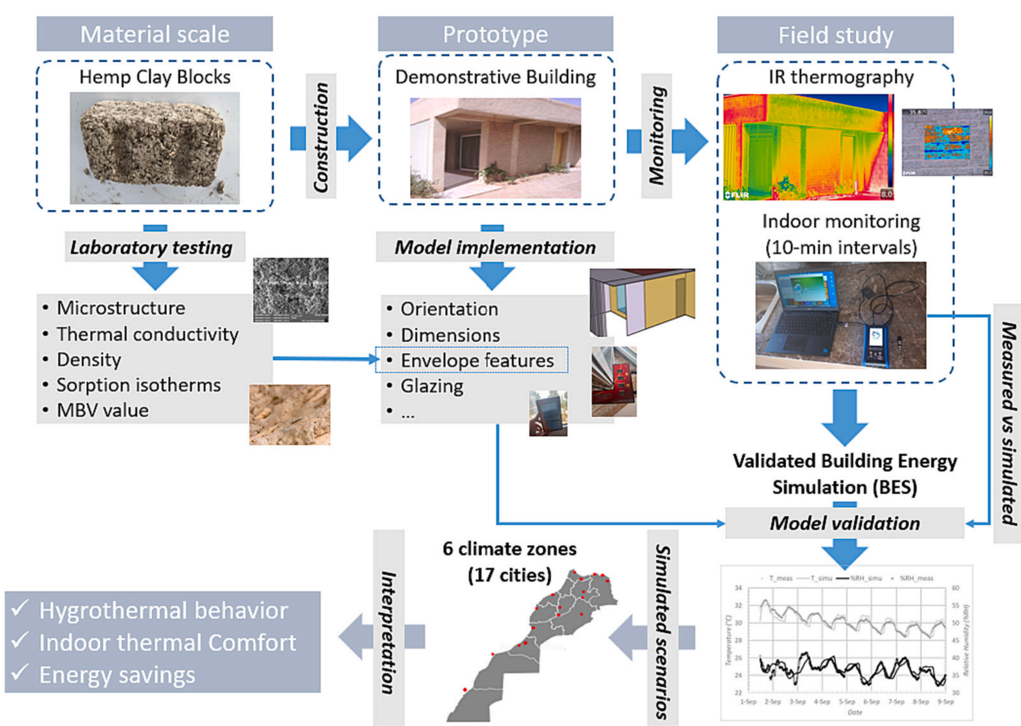


Fig. 1. Present research methodology overview.

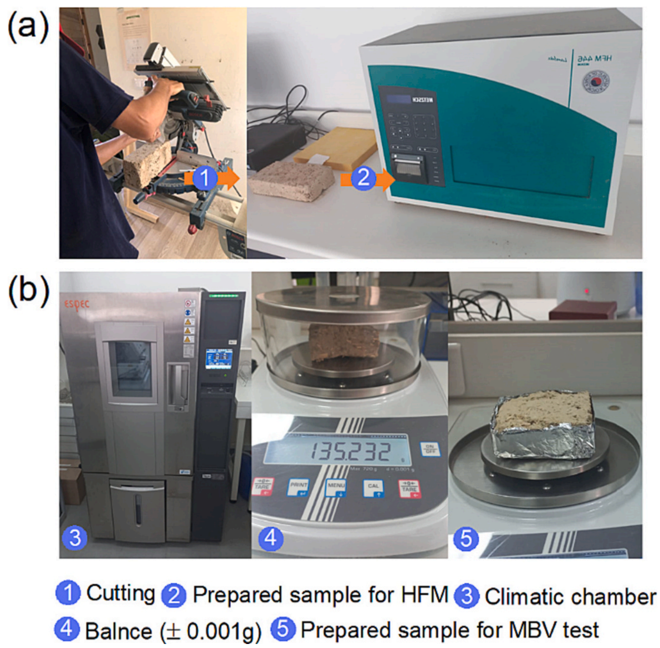


Fig. 2. Setup for Laboratory testing of hemp-clay blocks: (a) thermophysical and (b) hygric properties.

surfaces and conditioned at room temperature of 23 ± 0.5 °C and relative air humidity of 55 ± 4% for 24 h. The samples were tested at a range of mean temperatures from 0 °C to 45 °C, with a temperature difference delta of 20 °C. Sorption isotherms and moisture buffering value of clay-hemp blocks were identified as per EN ISO 12571 [39] and NORDTEST protocol [40], respectively. Detailed measurement protocols for both techniques can be found in [41,42].

Fig. 3 provides a summary of the experimental findings obtained from three samples of hemp-clay bricks after undergoing a 4-year exposure to outdoor conditions. As expected, there was a linear correlation between temperature increase and thermal conductivity (Fig. 3 a), demonstrating the significant influence of climate conditions on the performance of the external building envelope. The results indicated a ~ 22% increase in thermal conductivity from the lowest to highest values measured at 0 °C and 45 °C, respectively. At a temperature of 30 °C, which corresponds to the average outdoor temperature during the field study period (refer to section 3.2), the thermal conductivity of the bricks in their current state, following four years of outdoor exposure, was around 0.31 W/mK. This finding aligns well with the results obtained by Laborel-Préneron et al. [43], who reported thermal conductivity values ranging from 0.2 to 0.3 W/mK for unfired clay bricks with hemp shives contents of 3–6%. However, the obtained value represents a 39.5% reduction in thermal performance when compared to the manufacturer's specified value of 0.19 W/mK. This deviation can be primarily attributed to the dependency of thermal conductivity on the temperature and moisture level of building materials. Notably, higher moisture levels lead to increased thermal conductivity in hemp-based masonry units, resulting in reduced overall thermal transmittance. This phenomenon is consistent with previous research, further emphasizing the significance of moisture content in altering thermal properties [36]. As a result, researchers and construction professionals must consider this characteristic when assessing the in-situ performance of buildings.

One notable advantage of hemp-based building materials lies in their capacity to effectively control moisture levels within a building, so the sorption isotherm curve and moisture buffering value of the investigated bricks were measured and depicted in Fig. 3 (b-d). Fig. 3 b reports the sorption isotherms of three hemp-clay brick samples. These sorption curves closely resemble the profiles observed in previous studies on hemp-based building materials [43–45], where moisture content was reported to be approximately 4–6% at high RH. Fig. 3 (c and d) illustrate respectively the change in mass for the last 3 cycles (10 cycles in total) and the average MBV value calculated for three samples. Similar mass changes were observed for Rice husk-earth-based composites developed for building refurbishment [46]. MBV measurements of the investigated hemp-clay bricks indicated an average MBV value of 2.25 g/(m^2%RH), showing that the blocks exhibit excellent moisture regulation capacity (i.e., MBV > 2 g/m^2%RH [47]). When comparing the obtained value with literature results, the moisture buffer capacity of hemp clay bricks is in good agreement with values found by Mazhoud et al. [48] for hemp-clay composites (MBV ranging from 2.07 to 2.33 g/m^2%RH). The authors also highlighted the effectiveness of hemp clay composites as excellent hygric regulators and good insulation materials. A link has been reported between the high moisture buffer capacity, sorption abilities, thermal insulation quality and the microstructure (i.e. micro and macro porosity) of building material composites. The visual appearance and microstructure of hemp clay bricks are shown in Fig. 4. In addition to the microporous structure of the hemp's fibers, the images clearly show a higher interstitial porosity in the hemp clay samples, which explains the good hydric characteristics and excellent buffering capacity of the bricks [49].

3.2. Field measurement

Prototype description. The investigated demonstration building is a one-story detached single-family structure dispatched on a 52-m^2 ground floor area with a 3 m height to ceiling. The structure is located in the Green & Smart Building Park research platform in Morocco's Benguerir City. The building is primarily constructed from hemp clay blocks as shown in Fig. 5, where the exterior and interior walls are made from 30 cm thickness of clay hemp-based blocks. The components of the opaque envelope-thermo-physical properties were taken from BINAYATE Perspectives. Knowing that BINAYATE is a Moroccan software that enables controlling compliance with the Moroccan Thermal Regulations for Constructions (RTCM) [50]. Table 1 summarizes the main specifications of the hemp-clay studied building.

Indoor Climate. The case study building was monitored for one week in each of the bedroom and the living room thermal zones. The monitoring was conducted using a temperature and humidity probe type RH-AS2 connected to an AdvancedSense data logger developed by GrayWolf Sensing Solutions [51]. The RH-AS2 sensor has a temperature operating range of 0–50 °C as well as a humidity range between 0 and 100 %RH with approximately ±2 %RH accuracy. Moreover, as stated in Table 2, the bedroom was monitored first from the 25th of August until the 1st of September, then the monitoring system was placed in the living room from the 1st of September until the 9th of September. In the end, each thermal zone was monitored for 7 days. Moreover, the building does not dispose of any HVAC system. The building has remained unoccupied during the monitoring period, therefore there exists no energy use coming from electrical equipment and HVAC systems.

The opaque building envelope thermal characteristics were measured using the HFM device, whereas the hygric characteristics were measured using the MBV test, as explained before in Fig. 2. Moreover, the glazing properties were also verified and measured using glazing devices [52,53], enabling the detection of glazing type, layers thickness, SHGC, and VLT parameters. This helped measure the real building parameters including the envelope characteristics before the development of the numerical BEM. Furthermore, thermographic images were taken using a thermal imaging IR camera model FLIR T600 in order to detect temperature differences and building material behavior. The thermographic images were taken during the temperature peak hour at 12:00 PM for the both studied thermal zones in different wall facades. Table 3 summarizes the main specifications of the instruments of measurements used in the aim of this study including the temperature and humidity sensor, the window energy profiler, the glass thickness meter & Low-E

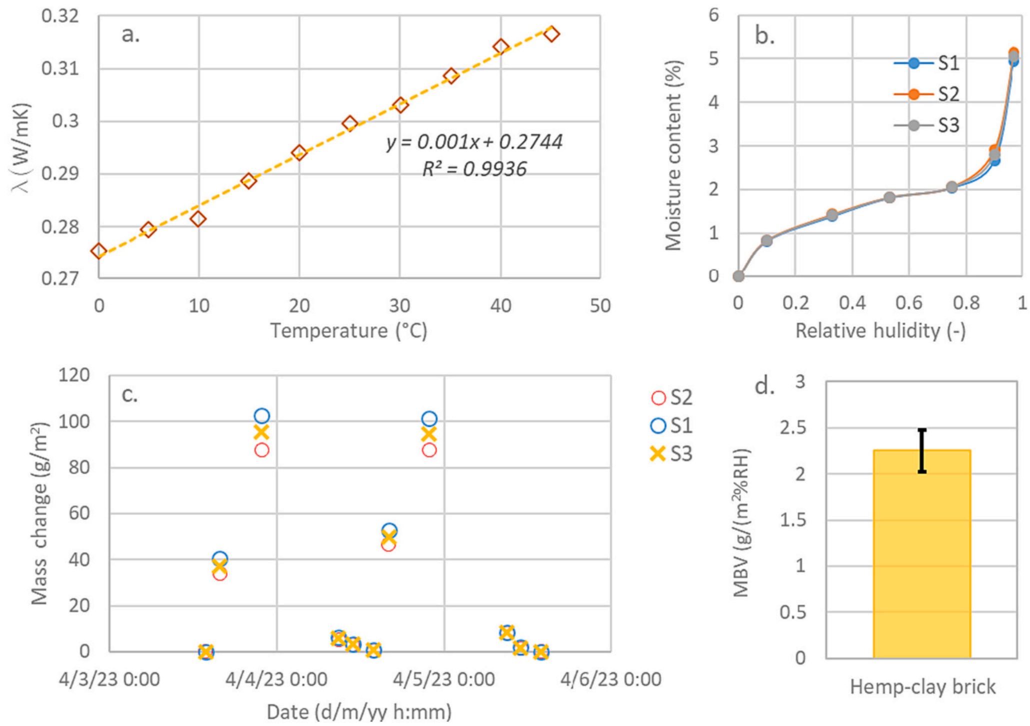


Fig. 3. Experimental characteristics of hemp clay bricks: (a) thermal conductivity vs temperature, (b) sorption isotherms, (c) mass change for three last %RH cycles and (d) moisture buffer value MBV.

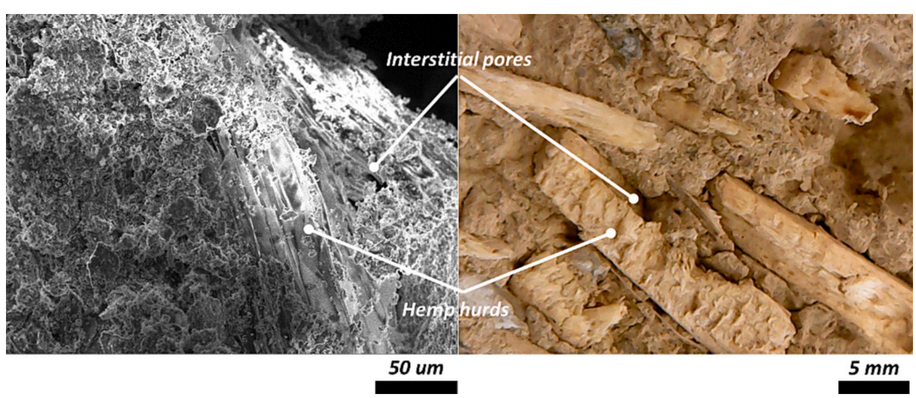


Fig. 4. Digital imaging – cross-section (right) and SEM (left) of a hemp clay block specimen.

coating checker as well as the thermal imaging IR camera.

Outdoor Climate. The studied building is located in Benguerir City under the hot semi-arid climate. Fig. 6 presents the solar radiation, air temperature, relative humidity, wind speed and direction of Benguerir City during the period of building monitoring. The maximum solar radiation reaches approximately 1000 W/m^2. The outdoor air temperature in the monitored period varies between 18 and 40 °C, whereas the relative humidity varies between 20 and 90 %RH.

Besides the baseline location in Benguerir City, five other locations are considered in this study to represent the main Moroccan climatic zones including many other cities in different Moroccan regions. Therefore, the localization of these 17 simulated cities on the Moroccan map is presented in Fig. 7. These simulated cities were chosen based on the most populated cities existing in each climatic zone, as well as the availability of meteorological weather stations. Nevertheless, contour maps are generally used in our study to visualize the results of the 17 cities. While, also projecting the results on the other non-simulated regions, by doing the kriging spatial interpolation in Rstudio [54,55]. However, the reliability of the contour map is highly influenced by the number of simulated cities, in the south regions of Morocco there is a lack of local meteorological weather stations. Therefore, the contour map was based on the maximum number of possible cities. Furthermore, Table 4 summarizes the main geographical, meteorological, and weather data of the selected studied 17 cities dispatched on 6 Moroccan climatic zones according to the Moroccan Thermal Regulation of Construction [50]. The choice of the representative cities of each Moroccan climatic zone was based on Binayate software. The first 15 cities' weather files were extracted using the onebuilding.org project, whereas Laayoune and Dakhla weather files were taken from Meteonorm software.

3.3. Simulation study

Building Model Implementation. The building energy model of the case study building was created using the EnergyPlus simulation engine. In the aim of this study, two BEMs were developed in order to compare the environmental, indoor thermal comfort, and energy use performances of the hemp-based constructions compared to the reference

Fig. 5. Demonstration building (left) and hemp clay blocks (right) of the present case study.

Table 1
Specifications of the case study hemp-based single-family building (construction elements from outside to inside).

Location	Ben Guerir (32.21 N, −7.93 W)
Construction area	52 m^2
Height	3 m
Orientation	East facing
Composition	1 bedroom, 1 living room, and 1 bathroom
Exterior wall area	103 m^2
Window-to-wall ratio	10%
Wall construction	30-cm hemp clay blocks. U-value: 0.661 W/m^2K
Roof construction	5-cm screed +3-cm roof membrane including coating +12-cm Hourdis slab +1-cm cement mortar. U-value: 2.021 W/m^2K
Floor construction	10-cm stone +4-cm reinforced clay +5-cm screed +2-cm tile. U-value: 1.988 W/m^2K
Window type	Double pane with no metal frame, glass air gap configuration 8.6/8.6 mm glass and 5.5 mm air gap. Visible (81%), UV (0%), infrared (50%), SHGC: 67%. U-value: 2.56 W/m^2K
Front door	Oak door. U-value: 2.995 W/m^2K
Infiltration	0.2 Air Change per Hour (ACH)
Number of people	Unoccupied during field measurements period (0 people)

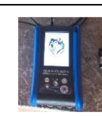
Moroccan constructions in 17 cities all over Morocco. The first base model developed describes the hemp-clay studied building, whereas the second model was based on typical Moroccan building construction without the use of hemp blocks in the building envelope. The building construction materials of the typical reference building, shown in Table 5, were extracted from a previous study by Dlimi et al. [56]. The steady-state thermal transmittance (U-value) is provided to present a theoretical value, which can be compared and verified in accordance with specific threshold values for steady-state thermal transmittance (U-value) as per Moroccan regulations [50]. Still, in the numerical simulation, the EnergyPlus engine takes into account the dynamic thermal properties and is quite accurate compared to the simple hourly methods [57]; such as EN ISO 13790 and EN ISO 52016–1, that perform dynamic thermal calculations according to the EN ISO 13786 standard. Besides, the developed 3D model along with the building plans are presented in Fig. 8.

For the building material performance evaluation, the baseline and reference numerical models were developed without the use of any

Table 2
Monitoring period description.

Space	Monitoring period		
	From	*To*	*Total*
Bedroom	25/08/22 at 00:09 AM	01/09/22 at 9:19 AM	7 days
Living room	01/09/22 at 12:49 AM	09/09/22 at 00:09 AM	7 days

Table 3
Specifications of the measurement's instruments.

Instruments	Model	Specifications	Picture
Temperature & Humidity Sensor	ID-610Xtra Data Logger Probe RH-AS2	- Temperature range: 0 °C – 50 °C. - Humidity range: 0%RH – 100%RH. - Accuracy: ± 0.5 °C & ± 2%RH. - Resolution: 0.1	
Window Energy Profiler	WP450	- Thick: up to 4.15″ - UV: Up to 365 nm. - Visible: 400–700 nm full spectrum. - Infrared: Up to 950 nm	
Glass thickness meter & Low-E Coating checker	GC3001	- Operating temperature: 0 °C - 40 °C. - Accuracy: Glass 0.2 mm / Air 0.3 mm. - Min glass thick allowed: 2 mm. - Min air space allowed: 4.7 mm. - Max glass thick allowed: 12.7 mm.	
Thermal Imaging IR Camera	FLIR T600	- Temperature range: −40 °C - 650 °C. - Accuracy: ± 2 °C. - Thermal sensitivity: <0.04 °C at 30 °C. - Resolution: 172,800 pixels (480 × 360).	

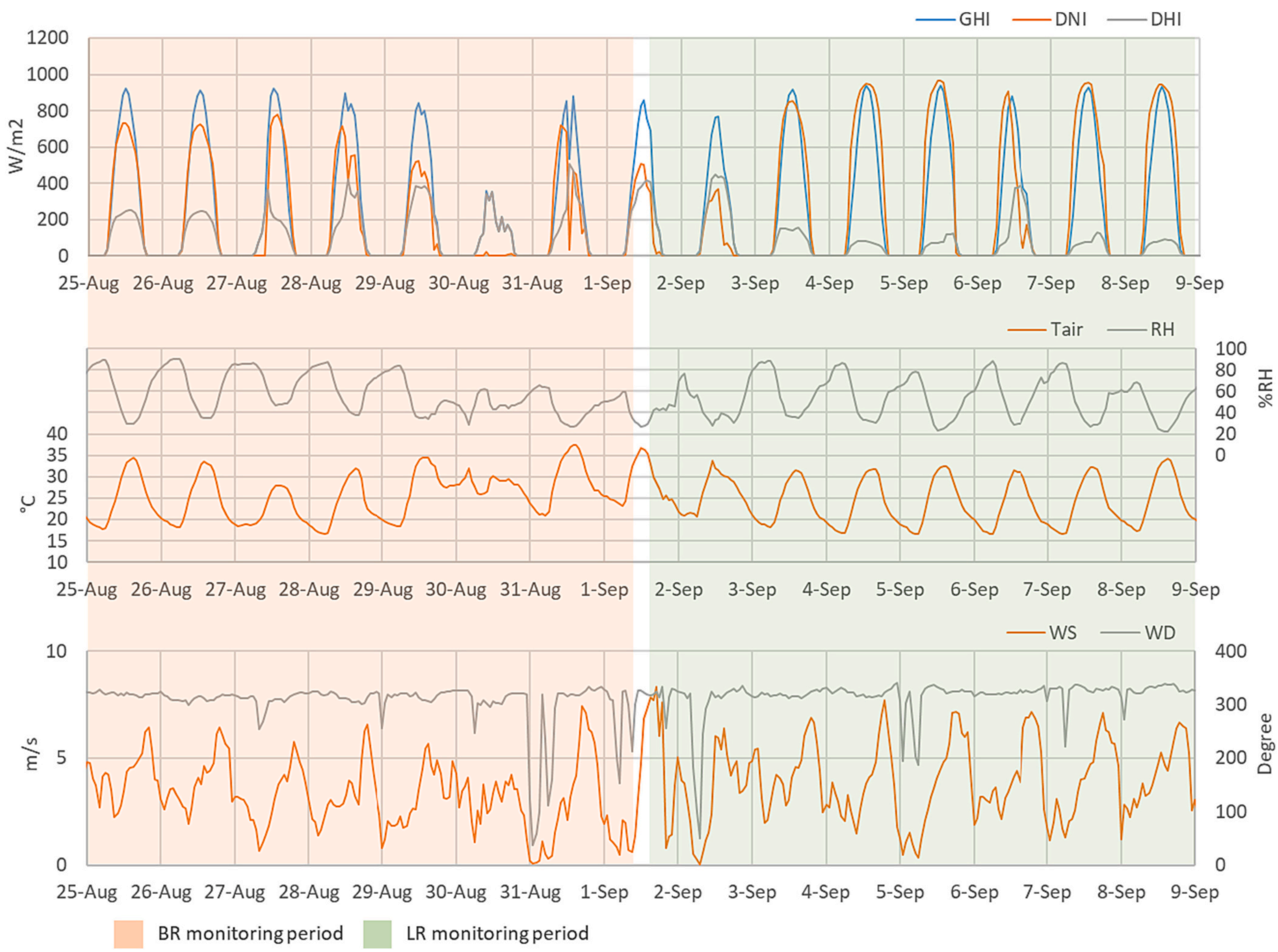


Fig. 6. Weather data of Benguerir City during the monitored period for BR (bedroom) and LR (living room).

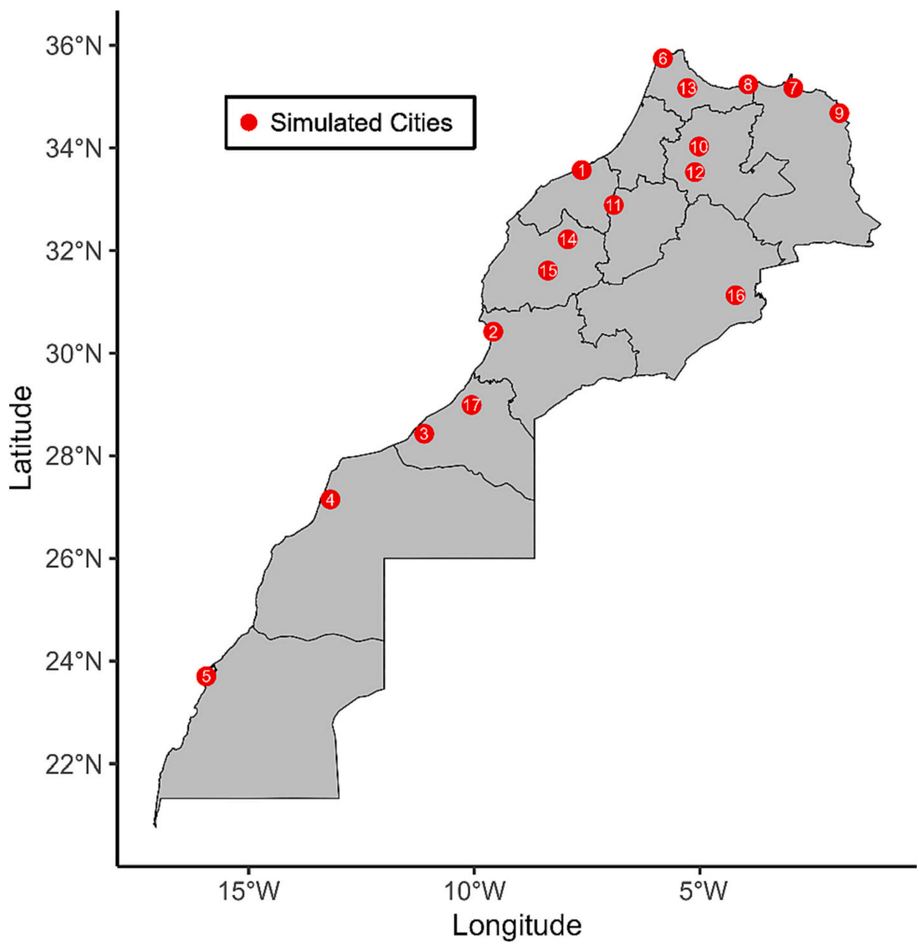


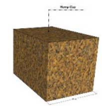
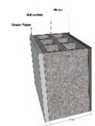
Fig. 7. Localization of the simulated cities in the Moroccan map.

Table 4
Summary of geographical locations, meteorological stations, and weather data of selected 17 cities in Morocco.

Climate	Location				Meteorological station		Summer characteristics		June			July			August		
RTCM	N°	City	Latitude (longitude)	KGCC	Station code	Elevation (m)	Highest daily DBT (°C) [month]	CDD** (°C.days)	GHI (Wh/m^2)	DBT (°C)	RH (%)	SR	DBT (°C)	RH (%)	GH (Wh/m^2)	DBT (°C)	RH (%)
Zone 1 - ***Atlantic***	1	Casablanca	33°35 N (7°36 W)	***Csa (warm Mediterranean climate)***	601,550	61	26.2 (July)	250.2	320.4	20.4	77.2	318.3	21.2	79.3	290.5	22.3	81.8
	2	Agadir	30°33 N (9°41 W)	***Bsh (Hot semi-arid climate)***	602,520	76	28 (August)	433.3	320.9	21.5	69.3	312.2	23.6	69.8	291.6	23.9	69.3
	3	Tan-Tan	28°45 N (−11°16 W)	***BWh (Hot desert climate)***	602,850	199	33.6 (August)	226.9	297.5	21.4	71.5	301.7	22.9	83.3	280.7	23.4	76.2
	4	Laayoune	27.15°N (13.19°W)		MN7 999 WMO	5	31.9 (July)	461.7	517	22	66	502	23	66	474	24	66
	5	Dakhla	23.69°N (15.94°W)		MN7 999 WMO	63	28 (July)	259.4	516	20	75	490	22	23	466	74	75
Zone 2 - ***Mediterranean***	6	Tangier	35°73 N (5°92 W)	***Csa (Mediterranean climate)***	601,010	18	30.4 (August)	427.2	310.9	21.5	69.2	325.1	24.0	64.5	293.9	25.8	64.0
	7	Nador	34° 99 N (3° 03 W)		603,400	177	30.2 (August)	410.0	322.7	22.2	63.0	318.3	25.4	56.9	288.7	25.8	62.4
	8	Hoceima	35° 18 N (3° 84 W)		601,070	27	29.3 (July)	347.3	323.4	22.0	74.3	322.7	24.5	63.0	289.6	25.3	76.1
Zone 3 - ***Continental***	9	Oujda	34° 78 N (1° 93 W)	***BSk (Cold semi-arid climate)***	601,150	467	32.2 (August)	617.1	324.1	22.7	53.4	314.5	26.7	59.5	286.0	27.2	59.3
	10	Fez	33°93 N (4° 97 W)	***Csa (Mediterranean climate)***	601,410	579	36.7 (July)	649.7	314.7	24.4	47.9	316.6	27.9	42.1	289.0	27.7	44.3
	11	Khouribga	32° 86 N (6° 97 W)		601,780	781	31.3 (July)	554.4	324.7	23.1	61.0	331.3	26.2	53.6	300.9	25.8	59.7
Zone 4 - ***Cold***	12	Ifrane	33° 51 N (5°15 W)		601,600	1663	28.8 (July)	232.7	314.3	21.2	56.3	313.1	23.7	46.3	287.7	23.7	46.4
	13	Chefchaoen	35°17 N (−5°31 W)		601,060	305	31.4 (August)	423.0	308.8	21.6	65.9	325.6	25.6	56.2	291.7	25.6	61.0
Zone 5 - ***Semi-arid***	14	Ben Guerir *	32° 14 N (7°56'W)	***Bsh (Hot semi-arid climate)***	602,051	422	34.2 (July)	749.2	307.5	23.2	53.3	320.4	27.1	46.6	290.2	26.9	49.9
	15	Marrakesh	31° 61 N (8° 01 W)		602,300	467	36.5 (August)	887.7	322.4	24.6	51.7	308.8	28.6	41.6	282.2	29.6	43.7
Zone 6 - ***Desert***	16	Errachidia	31° 55 N (4° 25 W)	***BWh (Hot desert climate)***	602,100	1044	35.4 (July)	1253	338.6	29.0	16.4	326.1	33.2	15.7	301.4	32.2	21.2
	17	Guelmim	28° 58'N (10° 4 W)		602,800	341	38.3 (August)	514.8	323.8	21.2	71.0	311.5	24.1	67.9	295.2	25.4	62.1

RTCM: The Moroccan Thermal Regulation of Constructions.
KGCC: The Koppen-Geiger Climate Classification, GHI: Global Horizontal Irradiance, DBT: average dry bulb temperature, RH: relative humidity.
* Prototype location.
** Celsius-based 15-year-average (2007 to 2021) cooling degree-days with a base temperature of 21 °C as per the Moroccan energy code.

Table 5
Building construction materials description (case study vs reference).

External wall	Materials[a]	Thickness (cm)	Pictorial Configuration	U-value (W/m^{2}K)
Case study	Clay hemp-based block	30		0.54[b]
References	Mortar Hollow brick Cement plaster	2 20 2		0.90[c]

[a] From the outer to the inner layer.
[b] Manufacturer [38].
[c] [56].

internal heat gains. Whereas, for the indoor thermal comfort and energy use performance evaluation purpose, the internal gains of occupancy and interior lighting were added to the numerical models as well as an ideal HVAC system with constant cooling and heating temperature set points. The building occupancy schedule was based on residential building scenarios, where occupants tend to work outside the building during weekdays. The used occupancy schedule was developed based on previous studies in the literature [58–60]. Table 6 describes the main input parameters specifications of the developed BEMs used for each evaluation scenario including the environmental performance, indoor thermal comfort, and energy use assessments. In the building performance evaluation, each of the indoor air temperature and relative humidity as well as time lag and decrement factor was assessed. Knowing that the time lag is a crucial metric of the thermal resistance of the building envelope and corresponds to the daily difference between the highest internal temperature and external temperature. Whereas, the decrement factor describes the percentage of when a temperature or a relative humidity peak is lowered by the time it reaches the interior surface of a construction element. Moreover, the indoor thermal comfort was evaluated using the calculation of the Predicted Mean Vote (PMV) indices respecting the recommendations of ASHRAE 55–2017 [61].

Building Model Validation. The accuracy of the numerical BEM was validated using indoor air temperature and indoor air relative humidity for two thermal zones of the building. The validation of the building energy consumption is not taken into consideration in this study, due to the non-existence of any electrical loads during the monitoring period. The validation strategy was performed based on the conducted real in-situ measurements of the building envelope. In that manner, the developed BEM could be accurate as much as possible with the real existing building. Moreover, the EnergyPlus simulation engine enables the validation of the indoor air temperature using the mass transfer model without taking into consideration the moisture and the heat transfer model for the validation of the indoor air relative humidity. Hence, in our case to validate the relative humidity, we have used a capacitance model as a simplified technique for figuring out the hemp clay internal relative humidity buffering based on a previous research conducted by Barclay et al. [62]. This capacitance model decreases the amount of moisture that enters the space by raising the air volume that the moisture is blended into. By using the EnergyPlus *Zone Capacitance Multiplier object*, the capacitance multiplier was configured to be equal to 5, as previously determined in [60]. Therefore, the validation conducted for both indoor air temperature and relative humidity for both existing thermal zones, the bedroom and the living room are respectively presented in Fig. 9, as well as the hygrothermal correlation between measured and simulated data. The validation findings show good agreements between measured and simulated data. Moreover, Table 7 proves that approximately 100% of indoor air temperature error data

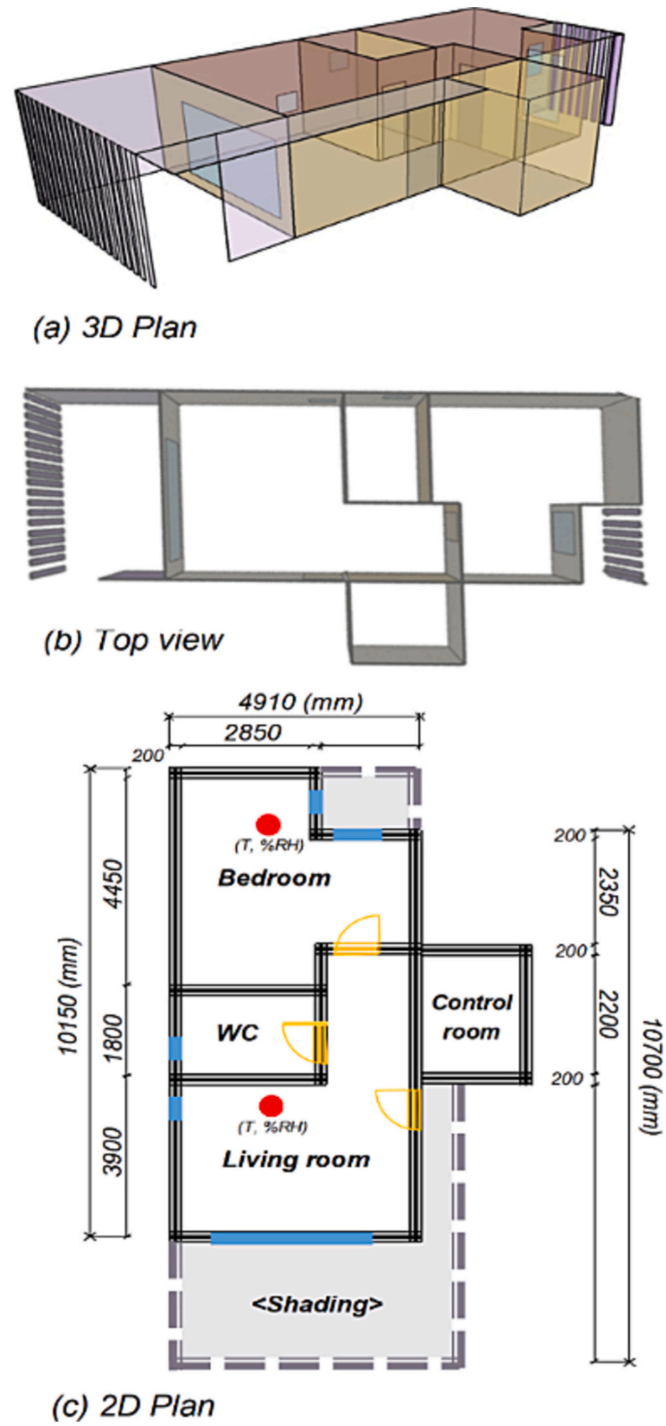


Fig. 8. Prototype drawings. (Red points) location of temperature and humidity probes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

are fewer than 2 °C for both zones, as well as 100% of indoor air relative humidity error data are <8%RH. Furthermore, following ASHRAE recommendations [63], the calculated CV(RMSE) of hourly data should be less or equal to 30%, whereas the calculated NMBE should be less or equal to ±10% for the hourly measured and simulated data in order to prove that the developed BEM is validated and calibrated. Thus, the statistical indices calculated for the aim of this study are respecting the thresholds given by ASHRAE guideline 14 for building validation [63].

Table 6
BEMs input parameters specifications.

Parameter	Unit	Value
Occupancy	m^2/person	10.4
Interior lighting	W/m^2	111
COP/EER[a]	–	3
Cooling set-point	°C	26
Heating set-point	°C	20
Clothing insulation	clo	0.5
Metabolism rate	met	1.2

[a] Energy efficiency of heating, ventilation, and air-conditioning (HVAC) system.

4. Results & discussion

4.1. Building material performance

Indoor Air Temperature. The indoor air temperature of both the hemp clay building and the reference building in the 17 studied cities of Morocco on the hottest day of the monitored period is presented in Fig. 10, as well as the temperature reduction between the hemp-based building and the reference conventional building. The findings show that in all cities the hemp clay building tends to have fewer temperature fluctuations during the day compared to the reference case building, which is having higher marge of temperature fluctuations. Moreover, based on the temperature reduction results, it is concluded that the hemp material is able to reduce the maximum indoor temperature starting from 1 °C until 6 °C, depending on the outdoor weather climate. For instance, in zone 1, the maximum temperature reduction can reach approximately 4.5 °C in Agadir City. Whereas, in zone 2, the maximum temperature reduced between hemp and reference case building is up to 5.5 °C in Nador City. However, in both zone 3 and zone 4, the hemp-based building has reduced the indoor air temperature by 6 °C compared to the reference building in both Fez and Ifrane Cities. Still, in zone 5 and zone 6, the maximum temperature reduced is 4 °C in Benguerir and Guelmin Cities. Therefore, based on these findings, the hemp material has proven its ability to reduce the daily indoor temperature fluctuation in all the different zone climatic existing in Morocco. This is attributed to the hemp material's good thermal conductivity, equivalent to 0.31 W/mK found by the conducted thermal conductivity laboratory testing.

Indoor Air Relative Humidity. The fluctuation of indoor air relative humidity on the hottest day of the monitored and validated period in the studied cities is presented in Fig. 11. According to these findings, the hemp is able to reduce and regulate the indoor air relative humidity in all the studied cities compared to the reference case building. When

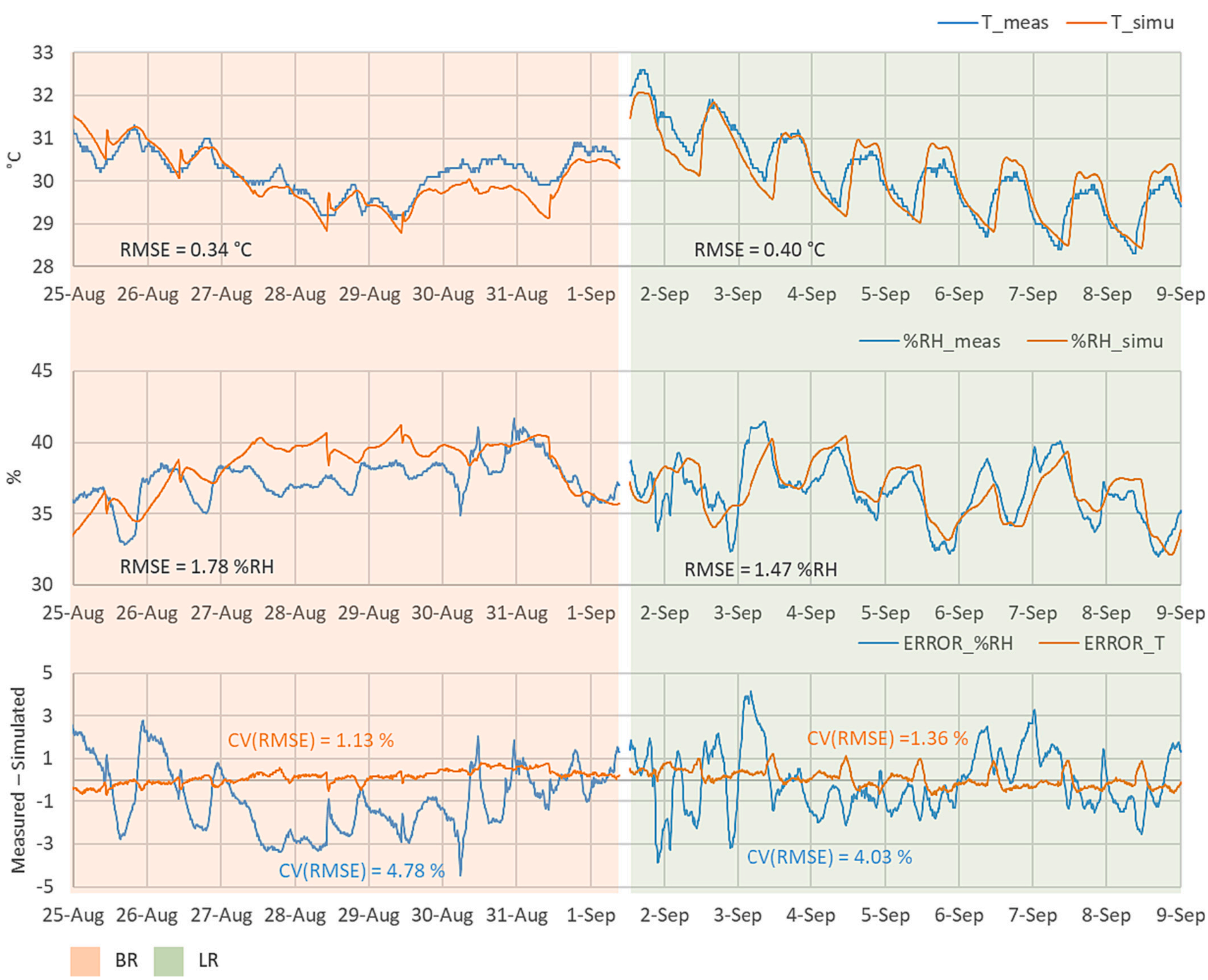


Fig. 9. Fluctuations and deviations of indoor temperature and relative humidity values for BR and LR (measured vs simulated).

Table 7
Hygrothermal correlations criteria.

Space	BR				LR			
Parameter	Temperature		Relative humidity		Temperature		Relative Humidity	
Residuals	*Criteria**	*In %*	*Criteria**	*in %*	*Criteria**	*in %*	*Criteria**	*in %*
	< 0.5	84.0	< 2	95.6	< 0.5	80.0	< 2	85.2
	< 1	100	< 4	100	< 1	98.5	< 4	99.8
	> 1.5	0	> 4.5	0	> 1.5	0	> 4.5	0
ASHRAE statistical indices	CV(RMSE)	1.13	CV(RMSE)	4.78	CV(RMSE)	1.37	CV(RMSE)	4.03
	NMBE	0.47	NMBE	−2.40	NMBE	0.20	NMBE	−0.27

* Measured – simulated.

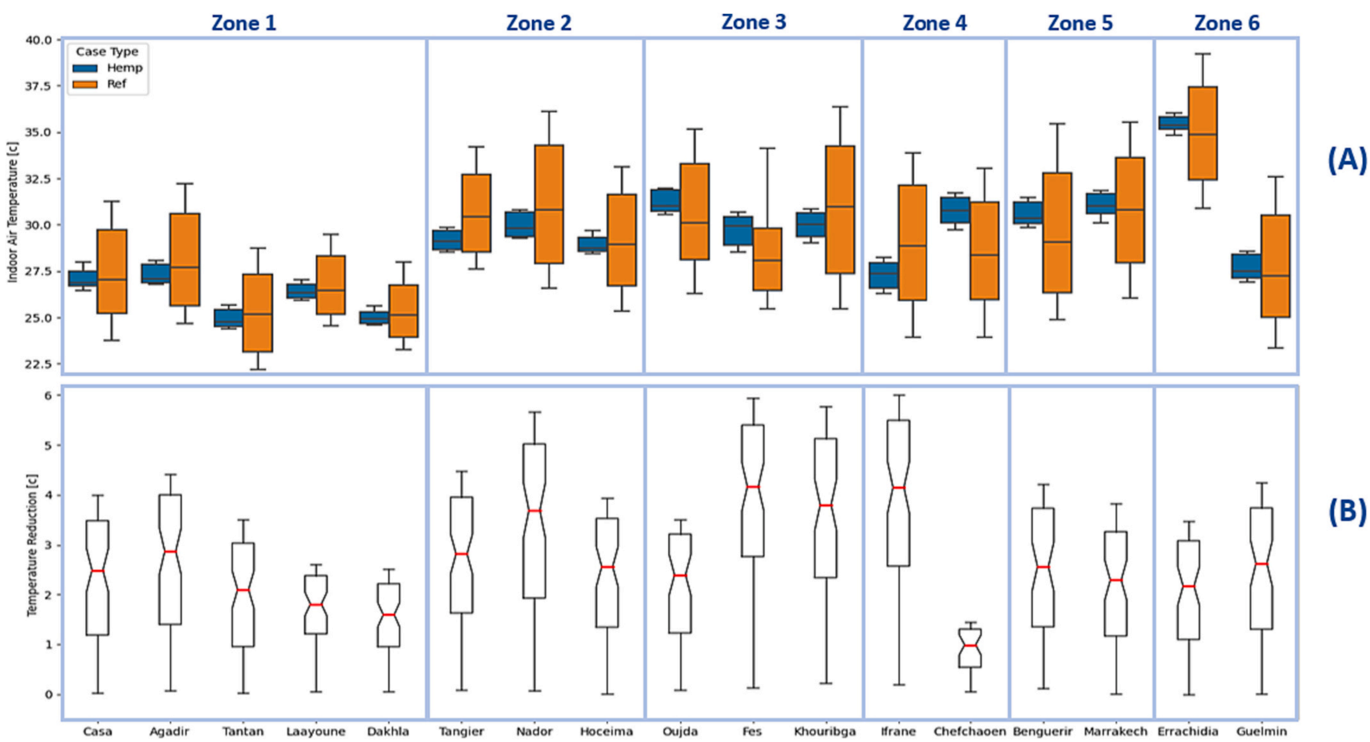


Fig. 10. Indoor air temperature variation for hemp and reference building (A), Temperature reduction between hemp and reference building in 6 climatic zones of Morocco (B).

using the hemp case building both the maximum and the minimum indoor relative humidity are less than the case with the reference building. However, the comfort zone of indoor relative humidity varying between 40 and 80%RH is not always met in the studied cities, hence the indoor relative humidity with hemp-based buildings tends to converge to the comfort and acceptable relative humidity zone. Therefore, the hemp material can be useful in reducing indoor humidity fluctuations in buildings as well as contributing to providing indoor comfort. This can be explained by the hemp material's excellent moisture buffering capacity, which was found to be equal to 2.25 g/m^2%RH.

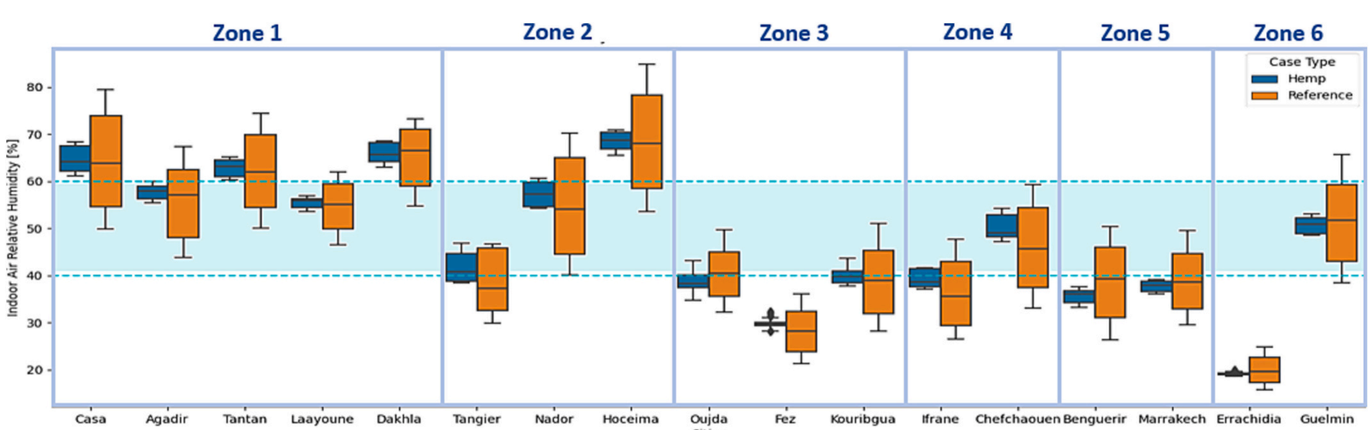


Fig. 11. Indoor air temperature variation for hemp and reference building in 6 climatic zones of Morocco.

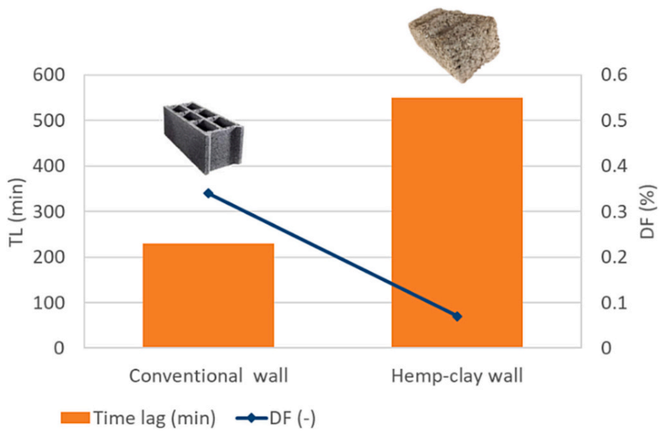


Fig. 12. Time lag and decrement factor for studied wall configurations.

Temperature Time lag. Fig. 12 presents the time lag as well as the decrement factor of the hemp and reference case buildings during the hottest day of the monitored period. The findings show that the hemp-based building is having the highest time lag equivalent to 9 h compared to the reference building with approximately 4 h. Moreover, the hemp clay building is also having a higher decrement factor than the reference case building. Therefore, when using the hemp clay building the highest indoor temperature reaches its maximum 5 h later than the case with the reference building. The ability of the hemp material of having both higher time lag and decrement factor is due to its low thermal conductivity, which enables the transmission of the outdoor air temperature into the building's indoor environment.

The thermographic images obtained using the IR camera for each of the bedroom and living room are presented respectively in each of Fig. 13 and Fig. 14 in three different facades for each thermal zone. The findings prove that the indoor surface temperature of the hemp-based wall is always lower than outdoor surface temperature for all the measured facades of both zones. The difference in surface temperature between indoor and outdoor is ranging between 3.8 °C and 18.9 °C for the bedroom and between 2.1 °C until 24.8 °C for the living room. Thus, the hemp clay material helps at reducing the peak indoor surface temperature in all the building orientations and thermal zones. This is due to the low thermal conductivity of the hemp material as well as its high time lag and decrement factor properties.

4.2. Thermal comfort evaluation

Fig. 15 presents the variation of daily indoor air temperature and relative humidity during the hottest day of the monitored period in 17 studied cities all over the 6 climatic zones of Morocco for both cases using the hemp clay building and the reference building with the presence of internal heat gains including occupancy and interior lighting. The findings prove that both indoor temperature and relative humidity are stabilized in the case of hemp compared to the reference building. For instance, in zone 2, the indoor temperature for the reference case is varying between 25 °C and 37 °C, whereas in the hemp case, the temperature varies between 29 °C and 33 °C. However, the indoor relative humidity varies in the range of 40–100%RH with reference case to 40–80%RH for the hemp-based building case. Moreover, Fig. 16 presents the variation of indoor thermal comfort using the PMV index in the studied cities during the hottest day of the monitored period with the use of an ideal HVAC system. The findings prove that the hemp-based building is able to provide indoor thermal comfort in the majority of the studied cities. Whereas, in the reference case building the PMV exceeds the acceptable ranges of the indoor thermal comfort. This is attributed to the low conductivity of the hemp material, which enables less impact of outdoor climate on the building's indoor environment. Therefore, this results in the conservation and low fluctuations of indoor air temperature and relative humidity. Thus, the material provides the building with indoor thermal comfort.

4.3. Energy use performance evaluation

The annual cooling and heating energy use of both the hemp-based

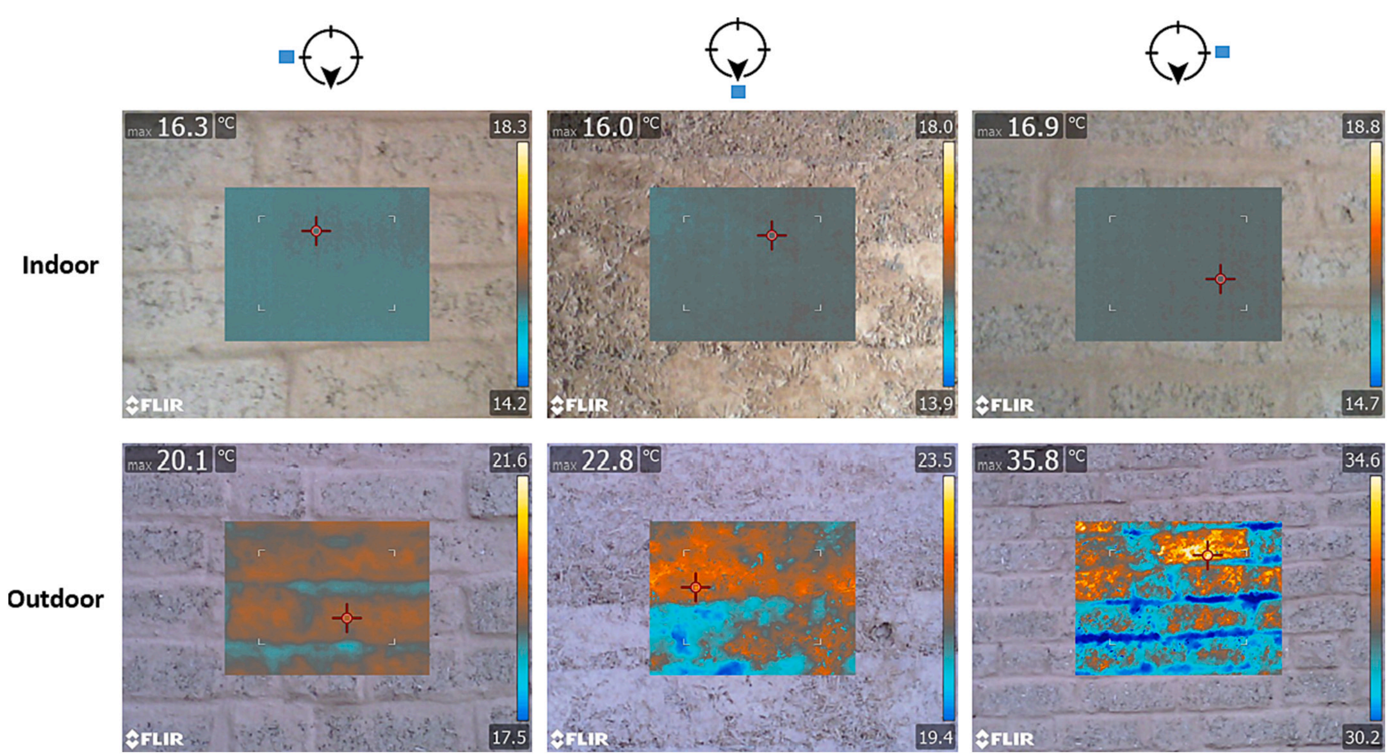


Fig. 13. Thermographic images of IR camera testing for BR in 3 different facades (Images taken at ~12.00 pm).

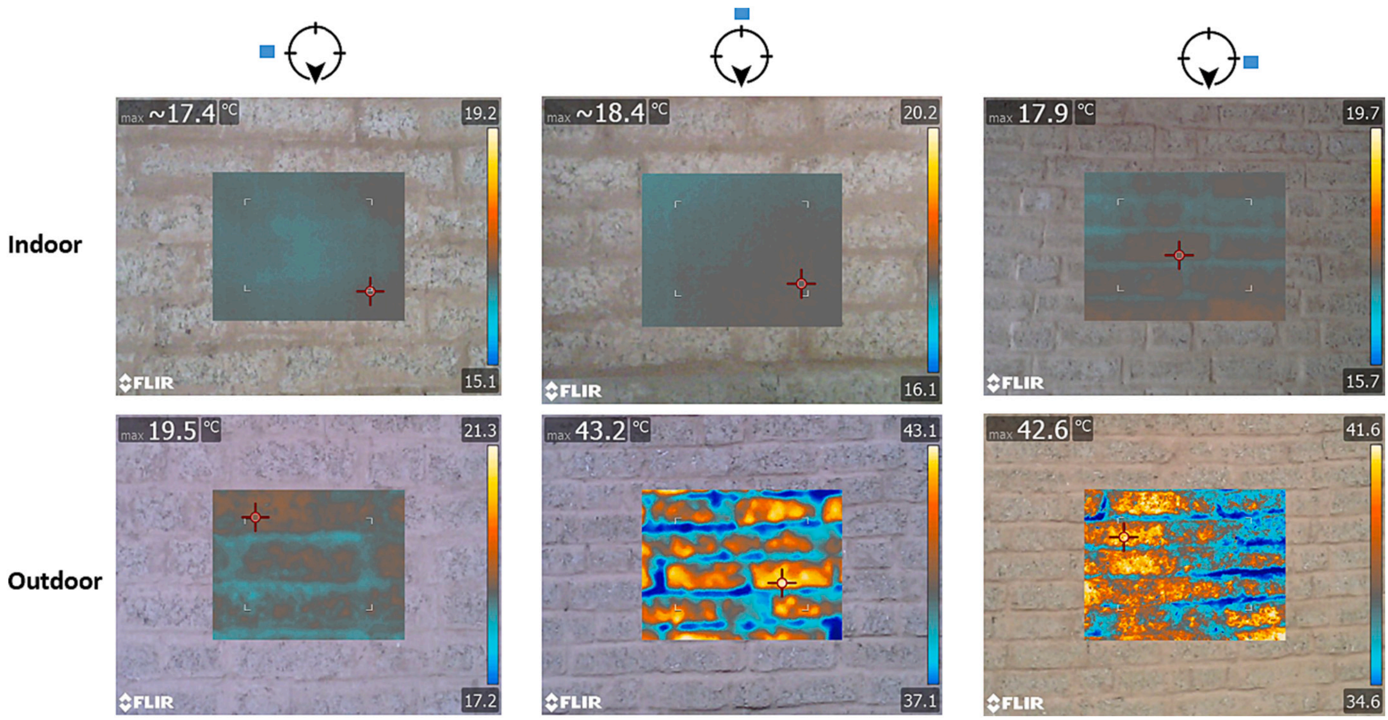


Fig. 14. Thermographic images of the IR camera testing for LR in 3 different facades (Images taken at ~12.00 pm).

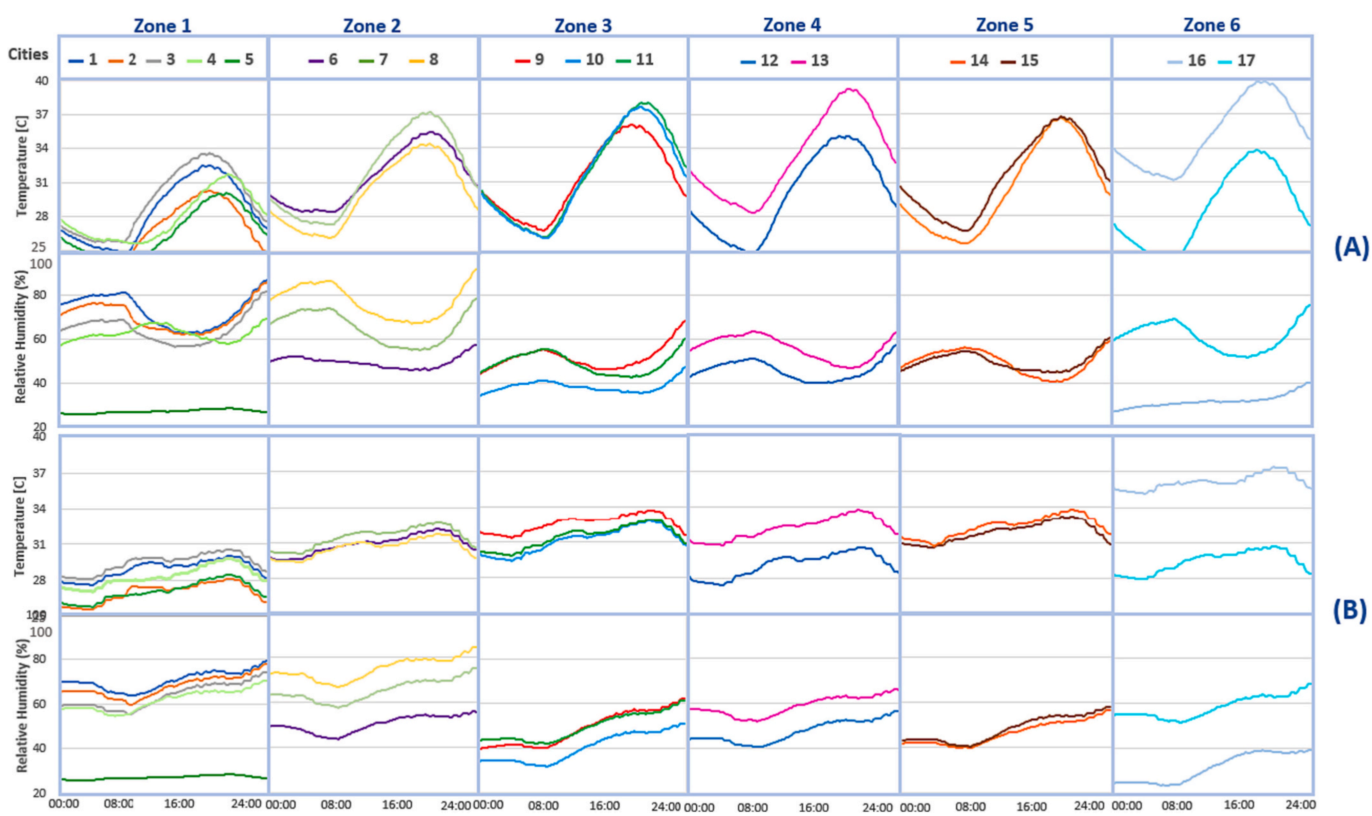


Fig. 15. Variation of indoor air temperature and relative humidity for the reference building (A), and hemp building (B).

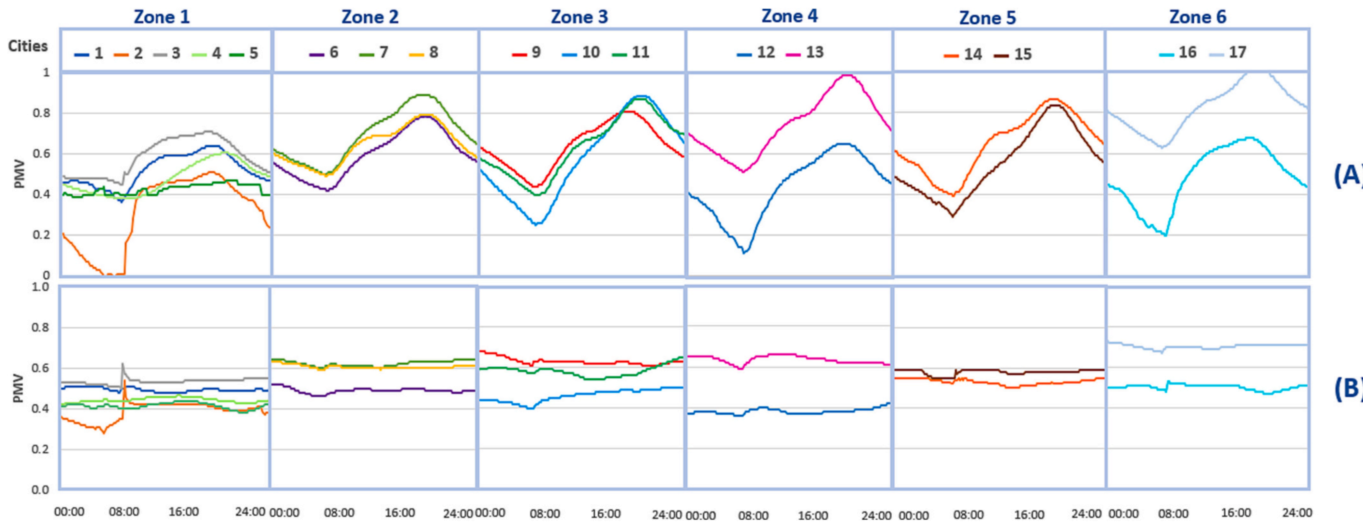


Fig. 16. Variation of PMV in the reference building (A), and in the hemp building (B).

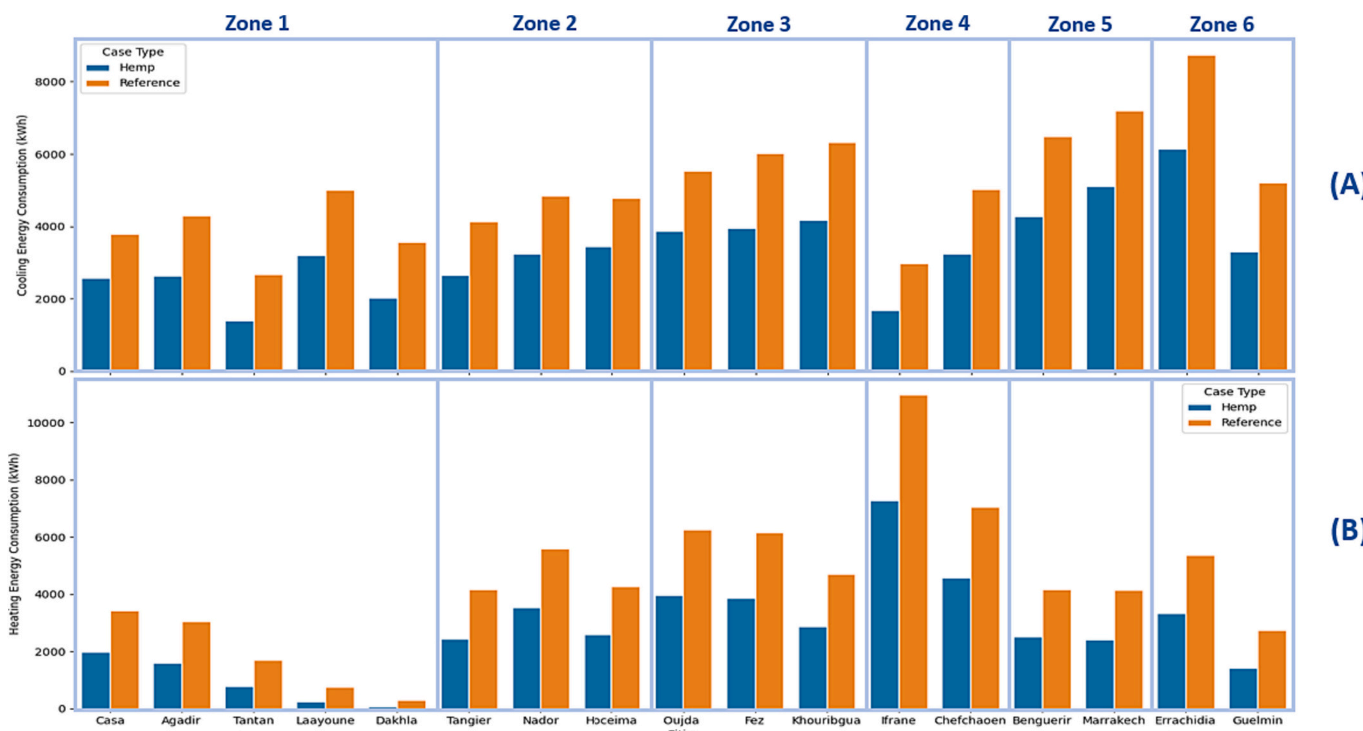


Fig. 17. Cooling energy consumption (A), Heating energy consumption (B) for each of the references, and the hemp building.

building and reference building cases in the 17 studied cities of Morocco are presented in Fig. 17. The results show that in all the investigated cities, the annual energy consumption for both cooling and heating of the hemp clay building is less than the annual energy use of the reference case building. For instance, Errachidia City has the highest annual cooling energy consumption compared to all the other studied cities due to its hot desert climate. So, in the reference building case, the cooling energy use of Errachidia City exceeds 8000 kWh, whereas the hemp-based building case reaches 6000 kWh of cooling energy. Furthermore, Ifrane City is the most heating energy-consuming city due to its Mediterranean Cold climate. Thus, Ifrane City consumes approximately 11,000 kWh of annual heating energy in the reference case building and 7000 kWh in the hemp-based building. Furthermore, the reason behind the ability of the hemp-based building to consume much less energy than the reference mortar-based building is related to the hemp material's good thermal conductivity and excellent moisture buffering, which results in reducing indoor environment fluctuations. Thus, the building requires less energy to provide indoor comfort levels.

The cooling and heating energy savings achieved when using the hemp clay building compared to the reference case building in all the studied cities are respectively summarized in Fig. 18 and Fig. 19. The findings show that the highest cooling energy savings are achieved in Tan-tan city with a hot desert climate. Whereas, the lowest cooling energy savings are present in Hoceima City with a Mediterranean climate. Moreover, the highest heating energy savings are reached in Dakhla City with an Atlantic climate with a rate of 79.82%. While the lowest annual heating energy savings are attained in Ifrane City with a rate of 33.71%. Therefore, the hemp-based building has great energy savings regarding

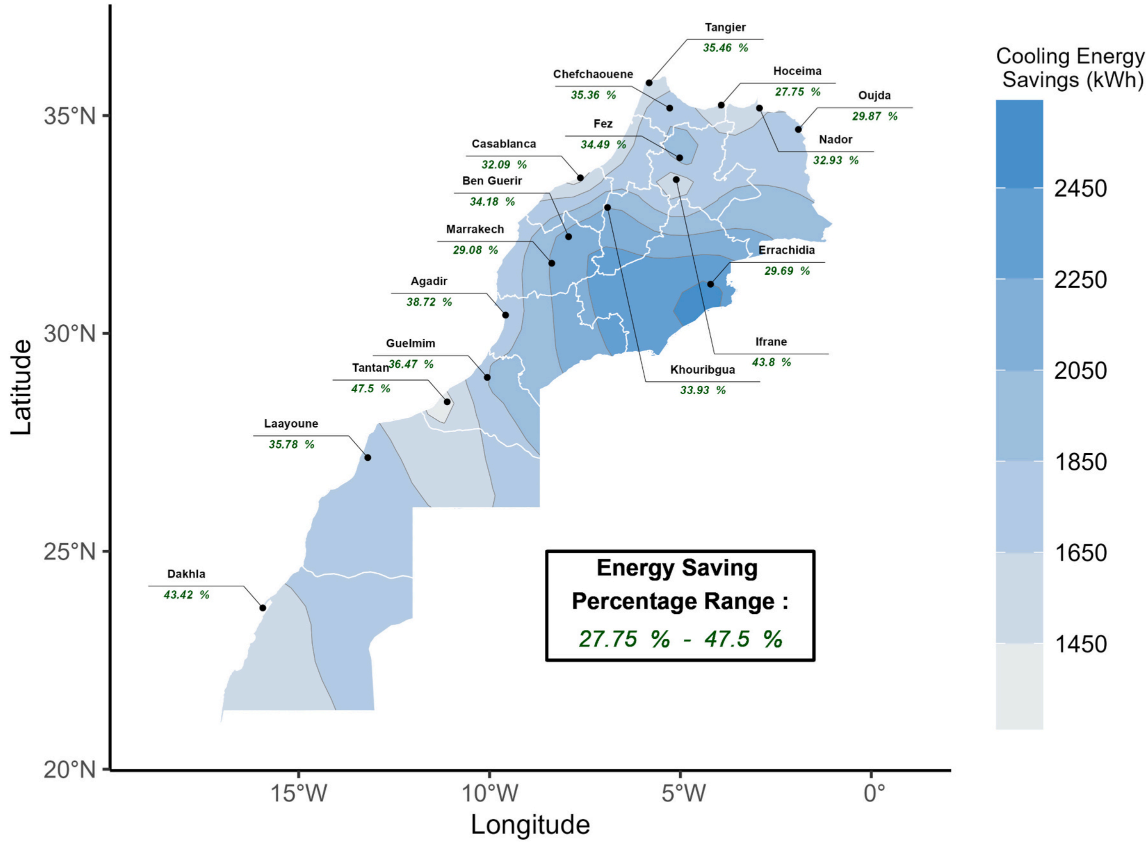


Fig. 18. Cooling energy savings.

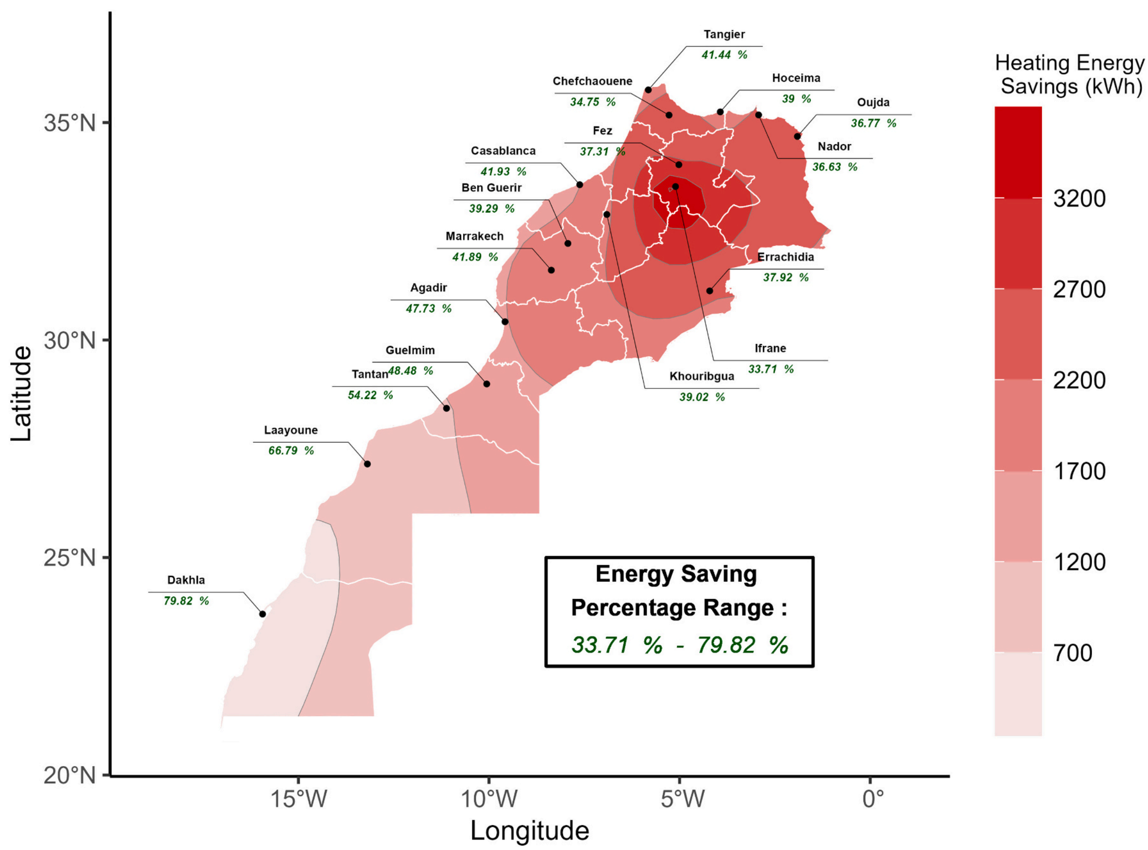


Fig. 19. Heating energy savings.

both cooling and heating energy needs all over the 6 climatic zones of the Moroccan country. Hence, the hemp material has shown great properties and behavior regarding the indoor building performance, the indoor thermal comfort as well as the energy use and savings in all the 17 studied cities all over the different climates existing in Morocco.

5. Conclusion

This study describes a detailed methodology of exploiting hemp material as an energy-efficient and eco-friendly construction material in the building sector, starting from the material scale to the building scale. The material scale part included in this paper dealt with a detailed characterization of hemp clay blocks including thermal and hygric properties specifications using HFM and MBV tests. Whereas, the building scale part deals with the monitoring of the real existing constructed hemp-based building along with its validation with the developed numerical building model. The numerical model validation was conducted using indoor air temperature and relative humidity measured and simulated data of two building thermal zones for one week. Then, many BEMs were created using 17 different weather files corresponding to different climatic zones existing in Morocco, in order to assess the hemp-based building material performance, the building indoor comfort as well the building energy use performance. The main conclusions obtained from this conducted study are listed below;

- The assessment of the indoor air temperature and relative humidity of the hemp clay building have provided lower fluctuations compared to the conventional reference building in all the 17 studied cities. Meaning that the hemp clay material blocks studied enable the regulation of indoor air temperature as well as relative humidity no matter the weather climate.
- The hemp-based building temperature time lag and decrement factor evaluation have demonstrated a 5-h difference between the maximum indoor temperature reached using the hemp clay building compared to the reference building.
- The thermographic images of the indoor and outdoor surface temperatures obtained using the IR camera prove that the indoor peak surface temperature of the hemp-based walls is always lower than the outdoor surface temperature, with a range of 2.1 °C to 24.8 °C for both studied zones in all the building orientations.
- The hemp clay blocks used in the constructed building have helped in providing indoor thermal comfort levels within the acceptable and recommended ranges compared to the conventional reference building in all the studied locations and climatic zones.
- The cooling and heating energy use of the hemp clay building is always lower than the energy use of the reference building. Therefore, the hemp clay material allows for achieving great cooling and energy savings all over the 17 studied cities of Morocco.

Hence, based on the findings of this paper it is recommended to encourage using hemp clay blocks in building constructions especially in the hot desert and semi-arid hot climates (ie. Zone 5 & 6) for more cooling energy savings, and in Atlantic climates (ie. Zone 1) for increased heating energy savings. Furthermore, it is also suggested to use hemp clay material as insulation layers in buildings due to its ability to regulate and insulation of indoor air temperature and relative humidity. Moreover, in the scope of the present paper, the investigated building was unoccupied and with no electrical loads including HVAC systems and electrical equipment. Therefore, the energy consumption and savings analysis was conducted numerically. Thus, in future work, we are planning to extend this methodology to another building with an integrated HVAC system in an occupied period. Furthermore, as a future perspective, the building envelope is also subject to be enhanced by developing multi-layer walls constructed from hemp-clay and phase change materials in order to evaluate the periodic thermal transmittance and assess its behavior and impact on such multi-layer walls. Moreover, the acoustic aspect of the hemp material is meant to be studied to assess the acoustic comfort of the occupants inside the hemp-based building. Since, in the current study, only the indoor thermal comfort of the hemp-based building was evaluated. Additionally, it is also recommended to conduct an economic analysis of the hemp material, to evaluate the affordability of the material in terms of investment costs and the payback period compared to conventional and commercial construction materials. An environmental analysis is also highly recommended to be assessed in future studies to present an overview of the CO2 emissions emitted and avoided when using hemp-based buildings compared to reference buildings.

CRediT authorship contribution statement

Niima Es-sakali: Methodology, Investigation, Conceptualization, Formal analysis, Software, Visualization, Writing – original draft. **Mouatassim Charai:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Samir Idrissi Kaitouni:** Writing – review & editing, Validation, Software. **Imad Ait Laasri:** Writing – review & editing, Visualization, Data curation. **Mohamed Oualid Mghazli:** Writing – review & editing. **Moha Cherkaoui:** Writing – review & editing, Supervision. **Jens Pfafferott:** Writing – review & editing, Supervision. **Sung Ukjoo:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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