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Learning from M'zab Architecture

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Fig. 1 Geographical location of the new Ksar Tafilelt relative to the old Ksar Beni Isguen

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A Strategy to Improve Comfort Level and Optimize the Thermal Behaviour of the Building

Learning from M'zab Architecture

energy efficiency
M'zab Valley, Ghardaia, Algeria
sustainability
thermal comfort
vernacular architecture

Due to centuries of rich experience, vernacular architecture offers significant lessons on sustainable building practices. This style competes exceptionally well with contemporary designs because of its efficiency, adept functionality, environmental compatibility, and harmonious relationship with human societies. The M'zab Valley in Ghardaia, Algeria, deserves to be classified as a World Heritage Site because it features original vernacular architecture that expresses smart building concepts while blending seamlessly into natural landscapes. In this paper, we validate the hypothesis that traditional Ghardaia housing in the Ksour reflects high energy efficiency and low reliance on active heating and cooling. We shall conduct a comparative study between a traditional dwelling belonging to vernacular architecture in the ancient Ksar Beni Isguen and a modern residence in Ksar Tafilelt. Through this comparison and simulation method, we seek to determine the most efficient architectural style in terms of energy use and the provision of thermal comfort in order to draw lessons and contribute to reducing the excessive consumption of non-renewable energies.

Introduction

Global challenges related to rising pollution levels and escalating costs associated with importing, exploiting, and distributing energy have pushed authorities to explore ways to better manage existing resources while curbing consumption. A key measure being considered is an investment in more sustainable construction practices (UNEP, 2022) for buildings and homes, as these sectors alone account for a staggering 40 percent of total global consumption, leading directly towards greater pollution (Lü et al., 2015).

As with many other countries, Algeria has seen a considerable rise in electricity demand nationwide. Especially when peak seasons occur. According to a report by the Algerian Ministry of Energy and Minerals, the recent changes in consumer preferences and their quest to improve the quality of life, combined with economic and industrial pressures, have contributed to this large and unusual increase in demand for electricity (MAEM, 2019). Moreover, it has caused great challenges for the energy industry in the country, as the building and construction sector tops the list of main energy consumers (Ghedamsi et al., 2016). With 47% of total national consumption, followed by the transport sector (29%), and finally, industry (24%) (MAEM, 2022).

In early July 2018, the province of Ghardaïa, located in southern Algeria, broke records for daily electric power consumption, with a peak consumption of 262 MVA out of the total allocations of 320 MVA to the province (reporters, 2018). This significant increase in consumption is mainly due to the widespread and excessive use of air conditioning, refrigeration, lighting, and water pumps, in conjunction with a severe heat wave that affected the region during that season (reporters, 2018).

There are various reasons why dwellings use more energy, especially in summer and winter, such as using a lot of non-provided electrical appliances and a lack of community awareness of the culture of rational consumption (Ghedamsi et al., 2016). In addition, architectural designs do not adhere to correct building practices in terms of good design, the ideal orientation of the dwelling, the distribution of space, and the use of building materials that provide thermal and acoustic comfort. How can we offer thermal comfort while taking advantage of passive strategies in construction?

Passive measures that include appropriate and correct orientation of buildings according to their location, good insulation of walls, openings, and ceilings, and an appropriate size of the outer envelope of the building remain effective and inexpensive solutions to improve the energy performance of buildings under construction and avoid the need to enhance internal comfort through continuous use of air conditioning and heating devices (Missoum et al., 2014). There is a need to work on taking the necessary measures to improve natural lighting and ventilation while limiting the transfer of heat from the outside through windows and doors (Santamouris and Dascalaki, 2002).

Building energy efficiency must be enhanced to improve economic performance by developing efficient solutions to reduce costs and expenditures directed at energy demand, thus protecting the environment, enhancing natural resources, and reducing harmful emissions. As a result, many governments and organizations are keen on enhancing the efficiency of buildings by providing legal and tax incentives to building owners and renters to increase their energy efficiency (Noailly, 2012).

We can enhance the comfort of residents in housing by implementing straightforward tactics. Some of these include enhancing the insulation of the building exterior, insulating the doors, incorporating a night ventilation system to expel air, utilizing a radiant heating system, and implementing shading techniques with the help of vegetation (Costa-Carrapiço et al., 2022).

Within this framework, adding thermal insulation, using movable shading devices, making windows bigger, and encouraging natural ventilation with ceiling fans can all help keep the temperature inside comfortable while lowering the need for cooling and heating and reducing energy consumption (Lozoya-Peral et al., 2023).

The majority of dwellings and structures built during the last four decades in Ghardaïa have low energy efficiency and are incompatible with the region's arid climatic conditions, which has led to an increase in the installation and operation of air conditioning and heating equipment and thus an unbearable increase in energy consumption expenditures.

Researchers, specialists, and practitioners of the construction sector in Ghardaïa realize the need to find radical solutions to restore the lost balance between architecture and nature, which was previously present in local traditional architecture. By encouraging scientific research in this field and reintegrating passive solutions and strategies into modern architecture in the region, we can raise the efficiency of buildings and structures and improve thermal comfort, reducing the increasing levels of pollution in the city.

A significant query we face is whether vernacular architecture in Ghardaïa can aid in creating efficient architectural methods that target energy reduction in buildings. We must research these traditional structures' energy efficiency and thermal comfort levels. Additionally, we should investigate and experiment with the techniques and strategies utilized in vernacular architecture to repurpose them intelligently and contemporaneously when planning new initiatives for the locality.

According to field research and technical computer modelling, the street temperature in Ksar Tafilelt in Ghardaïa is four times higher than in Ksar Beni Isguen. In addition, natural night ventilation in traditional mansions is the most effective passive cooling method in domestic dwellings throughout the hot summer months (Telli et al., 2020).

Another study showed that, based on the measurements taken at the site, the role of roofs in controlling temperature changes and ensuring appropriate and acceptable thermal comfort was verified in the dwellings of Ksar Beni Isguen and Ksar Tafilelt. The results showed that the city of Beni Isguen provides excellent comfort during the winter season. However, the New Ksar of Tafilelt needed better thermal comfort, especially on the upper floor at night, exceeding the acceptable comfort range (Kadri and Bouchair, 2020).

Addressing our present situation necessitates enacting a sustainable architecture policy. This policy will ensure the optimal functioning of new construction while incentivizing citizens, including real estate owners and tenants, to embrace the solutions and technical innovations to enhance their property's efficiency levels and fix its faults. Encouraging greener alternatives like passive building technologies and renewable energies instead of irrational energy consumption is reasonable and crucial when pursuing an enduringly sustainable future.

To this end, it is important to use the knowledge accumulated from generation to generation about passive processes to improve thermal comfort while saving energy (Gandhi, 1980). Because, in contrast to modern constructions, vernacular architecture is more adaptable and harmonious with the temperature rise, especially in the summer, through its application of passive principles developed by previous generations. Examples of these principles include the correct orientation of the plan, ideal dimensions and shape of the building, and climatic components such as balconies, wind catchers, central courtyards, etc. (Ibrahim Momtaz and Abd El Kader, 2012).

The main objective of this paper is to explore and understand the local architectural style suitable for the region's environment and its effectiveness in terms of energy efficiency (electricity and natural gas consumption) and thermal comfort standards. In order to achieve the goal mentioned above, we conducted a comparative analysis between two dwellings in the city of Ghardaïa: one representing traditional architecture in the Ksar of "Beni Isguen" and the other showcasing modern architecture and structure in the Ksar of Tafilelt (an eco-city). The acquired results from this study will validate the hypothesis that vernacular architectural style secures tremendous capabilities in reducing energy consumption, minimizing waste, and ensuring pure satisfaction with the surrounding environment in dwellings, particularly in terms of human thermal comfort. These outcomes will also pave the way for further research in the upcoming future to identify and determine optimal strategies inherent in the most successful architectural style. In other ways, this will allow and help the study of the integration of current and new technologies to adapt and update residential projects and future facilities in the local region and contribute to a more sustainable future.

Methods

The study began with a comprehensive review of existing literature, focusing on global strategies and techniques employed in ver-

TABLE I A SUMMARY OF THE METHODOLOGY EMPLOYED

1	Analytical Framework
2	Comparison of Ancient and Modern Vernacular Architecture
3	A Comparative Study of Dwellings
4	Performance Assessment and Building Energy Modelling
5	Data Analysis and Conclusion

nacular architecture. This literature review aimed to understand the diverse approaches used in different parts of the world and their potential influence on energy efficiency and thermal comfort within buildings.

• Analytical Framework – A set of research tools (listed in Table I) and an analytical methodology were both used. This approach laid the foundation for subsequent analyses and comparisons.

• Comparison of Ancient and Modern Vernacular Architecture – The study conducted a comparative analysis between the ancient Ksar of Beni Isguen and the modern Ksar of Tafilelt, both representing vernacular architecture in the Ghardaïa region. An analysis network was constructed to identify and assess the strategies and tactics applied in desert Ksour[1], with a focus on understanding the evolution and adaptation of architectural principles.

• A Comparative Study of Dwellings – A comparative study was carried out on two dwellings with distinct architectural styles but similar technical specifications. These specifications included factors such as location, orientation, area, number of floors, number of family members, quality of equipment, and consumption patterns. One dwelling was from Ksar Beni Isguen, while the other was from Ksar Tafilelt in Ghardaïa.

• Performance Assessment and Building Energy Modelling – To evaluate energy efficiency and thermal comfort, building energy modelling and performance assessments were conducted using specialized software tools. Autodesk AutoCAD, EnergyPlus, and Designbuilder were employed to simulate and analyse energy consumption and thermal comfort of selected dwellings. This step aimed to identify the architectural style demonstrating superior efficiency in terms of energy consumption and thermal comfort quality.

• Data Analysis and Conclusion – Data collected from the literature review, comparative analyses, and simulation results were analyzed to draw conclusions regarding the impact of vernacular architecture on energy efficiency and thermal comfort. The findings contribute to a deeper understanding of the strategies and tactics that can be applied in designing energy-efficient and thermally comfortable buildings, particularly in arid regions like Ghardaïa.

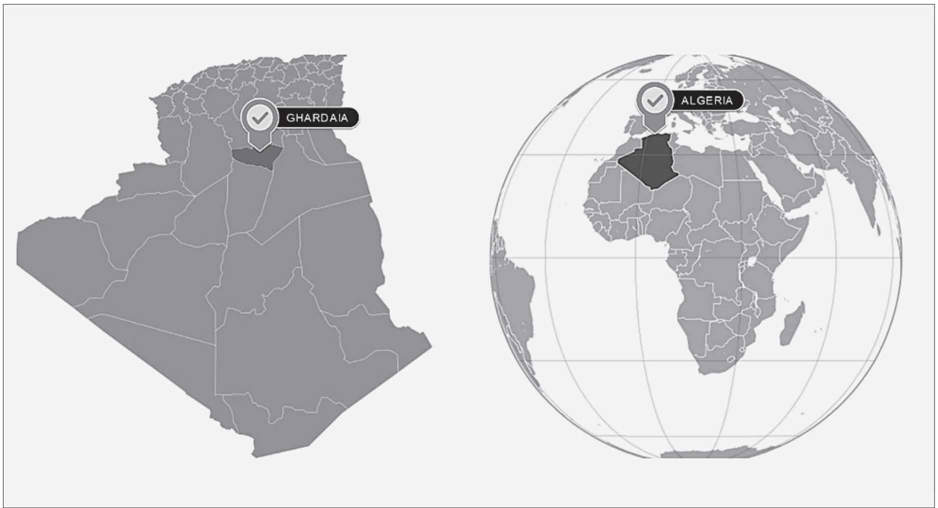


FIG. 2 GEOGRAPHICAL LOCATION: ALGERIA, GHARDAÏA

DESCRIPTION OF THE CASE STUDY BUILDINGS

Etymologically, a ksar is a fortress, or more precisely, a fortified city equipped with defensive structures. It is also a natural and social environment with unique urban and architectural features (Gueliane, 2019). The case study is represented by two individual residences located in the city of Ghardaïa, south of Algeria (Fig. 2), with an arid desert climate (Gairaa, 2010).

The first dwelling is traditional in Ksar Beni Isguen, representing the vernacular architecture of the region (coordinates: 32°28'25"N, 3°41'39"E. altitude: 522 m), The Ksar of Beni-Isguen, founded in 1350 (OPVM, n.d.-b), is situated on the slope of a peak, the same distance between the Ksar of Bounoura and the Ksar of Melika in Ghardaïa (OPVM, n.d.-a). The general area of this ksar is estimated to be 16.5 hectares, with a total of 1010 houses (Chabi, 2009). Moreover, the second is a modern dwelling in Ksar Tafilalt Tajdite (coordinates: 32°27'38 N, 3°41'19"E. altitude: 562 m). To meet the Mzab Valley's housing demand, the Beni Isguen community planned the new project as an extension (Fig. 1) to the old Ksar in 1997 (Diafat and Madani, 2019). The project was completed in 2011 on a 22.5-hectare plot of land and contains 1050 dwelling units for Mozabite young couples (Souidi and Bestandji, 2019).

• The weather conditions – Ghardaïa's climate is subtropical desert (hot and dry climate), with warm winters (though it can get cold at night) and sweltering, sunny summers (Fig. 3), where sandstorms are most common in the spring (Climate, n.d). The city has an average annual temperature of 23.29 °C, which is 3.29% higher than the national average. Ghardaïa gets about 3.51 millimeters (0.14 inches) of rain each year and has 12.46 rainy days (3.41% of the time) (Climate, n.d.-b).

1 Ksour is the plural of the word "ksar".

Investigative Tools

• Simulation softwares – To holistically examine energy consumption behaviours alongside thermal comfort considerations within our selected dwelling samples, we employed multiple cutting-edge software systems, including EnergyPlus™ v9.4.0, DesignBuilder v7.0.2.006, and Autodesk AutoCAD, to accurately model and simulate diverse variables.

• Model calibration and validation – In order to validate the energy consumption and demand results, a comprehensive and accurate verification procedure was implemented to ensure the accuracy of the data and the accuracy of research outcomes and conclusions. This involved calibrating the monthly energy consumption values obtained from simulating each building separately, one by one, with the actual utility bills for electricity and gas over the past three years. The whole purpose and aim were to identify any potential inconsistencies or deviations between the billed data and the simulated data, so in order to achieve this purpose, two primary metrics were employed: the Normalized Mean Bias Error (NMBE), the Root Mean Square Error (RMSE), and the Coefficient of Variation of the root CV (RMSE). All these metrics were selected in accordance with the recommendations outlined in ASHRAE Guidelines 2014-14 (ASHRAE 14, 2014). The calibration and verification processes used adhered to equations (1) and (3) (Makhloufi and Louafi, 2022).

$$MBE = \frac{\sum_{i=1}^{n} (Q_{\text{predi}} - Q_{\text{data}})}{nQ_{\text{data}}} \quad (1)$$

$$RMSE = \frac{\sqrt{\sum (Q_{\text{predi}} - Q_{\text{datai}})}}{n} \quad (2)$$

$$CV(RMSE)\& = \frac{RMSE}{Q_{\text{data}}} = \frac{\frac{\sqrt{\sum (Q_{\text{predi}} - Q_{\text{datai}})}}{n}}{Q_{\text{data}}} \quad (3)$$

Where:

MBE: Mean Bias Error

RMSE: Root Mean Squared Error

CV(RMSE): Coefficient of Variation of the Root Mean Squared Error

Qpred i: anticipated value for period i

Qdata i: measured value for the period i

Qdata: measured avg for the period

In accordance with ASHRAE Recommendations 14-2002, the acquired results from the monthly calibration and verification process had to exhibit an acceptable level of potential error:

NMBE should be equal to or less than 5%.

(CV) RMSE should be equal to or less than 15%.

We rigorously evaluated the measurements for MBE and CV (RMSE) following (Table II) under the guidelines of Guideline 14-2014. And the results obtained were accurate according to the above equations.

• Occupancy and operation schedules – Table III summarizes the occupancy and operating schedules that were used in the simulation process for the two dwellings.

Analysis Grid: Differentiated Strategies between Old and New

Ghardaïa's M'zab Valley serves as a nature incubator for a UNESCO World Heritage site that was categorized in 1982 by the organization (UWHC, n.d.). Five historical Ksour, constructed separately at different junctures along the route of M'zab Valley, are situated therein: Ksour El Atteuf, Bounoura, Ghardaïa, Beni Isguen, and Melika.

Vernacular architecture in the M'zab Valley is characterized by its adaptation to its natural surroundings (OPVM, 2012b). Moreover, its richness in many strategies and techniques compatible with the desert environment provided technical solutions to many challenges in the region.

These strategies were implemented in the context of vernacular architecture within the Ksour region. They were systematically acquired through a combination of field research and a comprehensive review of prior studies. Extensive conversations with influential figures in the region's history, architecture, and urbanism informed this data collection process, which depended on precise observation.

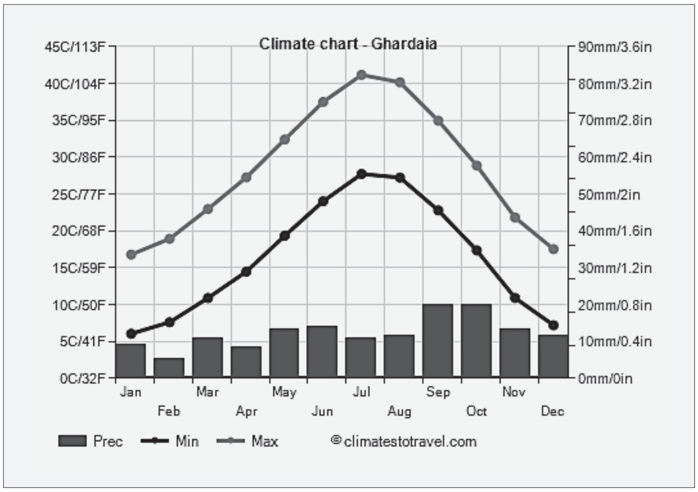


Fig. 3 Average temperatures and precipitation in Ghardaïa

Table II Calibration of results in accordance with ASHRAE 14-2002 recommendations

Indicators	(CV) RMSE	MBE
Percentage error	8,3%	0,43%
ASHRAE 14-2002 recommendations	≤15%	≤5%

Table III Occupancy and operation schedules

Issue	Simulation settings
Heating setpoint temperatures	21 C°
Cooling setpoint temperatures	25 C°
Infiltration	0,3 AC/h
Operating hours	14h
Days Schedules	7 days per week
Occupant density (dwelling Beni Isguen)	28,52 m²/person
Occupant density (dwelling Tafilelt)	33,97 m²/person
Equipment power density for the kitchen	30 W/m²
Equipment power density for living/bedroom	12 W/m²
Equipment power density for other spaces	5 W/m²
Outside air rate/person	8,1 L/s.person
Light power density	5 W/m²

TABLE IV THE COMPARATIVE TABLE OF ARCHITECTURE AND URBANISM STRATEGIES IN THE FORM OF AN ANALYSIS GRID

Indicators	Ksar of Beni Isguen	New Ksar of Tafilelt
Situation	The Ksar of Beni Isguen is situated on the slope of a hill, the same distance as the Ksour of Bounoura and Melika, and is close to water sources and oases (OPVM, n.d.-a).	Ksar Tafilelt, situated atop a hill, is 2.1 km away from the city of Beni Isguen. From this vantage point, one can enjoy breathtaking views of the M'zab Valley.
Construction date	In 1350 (AD) (OPVM, n.d.-b).	Starting date: March 13, 1997. It was inaugurated in 2007 (Tafilelt, n.d.).
Orientation	The local environment and defense requirements determine the ksar's orientation.	East-west and north-south are the two primary street directions (Chabi and Dahi, n.d.).
Form	The irregular form of Ksar Beni Isguen harmoniously follows the natural contours of the surrounding topography.	The form of Ksar Tafilelt is semi-regular, achieved by leveling the floors through soil excavation using specialized equipment during the construction process.
Defensive system	The ramparts are armed with watchtowers and gates (OPVM, 2015).	A symbolic defensive wall surrounds the Ksar.
Urban morphology	A very compact urban morphology	A compact urban organization
Housing density	61,21 dwellings/ha	46,66 dwellings/ha
Streets	The streets are narrow and winding, which follows the topography of the area (OPVM, 2015).	regular layout , hierarchical checkerboard type (Chabi and Dahli, n.d.)
Street dimensions	Usually three cubits wide (OPVM, 2014a). About 1,4 meters, but in certain instances, the width of the walkway may exceed 2 meters.	Streets and roads of adequate width have been adopted to allow the passage of vehicles, motorcycles, and bicycles.
Covered passages	Found in many places in the Ksar, these covered passages, located between two opposite buildings, provide a shaded area, are protected from the sun (OPVM, 2014a), and allow the passage of breezes.	The same strategy was implemented in Ksar Tafilelt, where covered passages can be found in various locations.
Oasis or the green spaces	The palm grove, located adjacent to the Ksar, serves as an agricultural area and also houses secondary residences that are primarily utilized during the summer season. The moisture emitted from the orchards played a crucial role in creating a soothing atmosphere within the Ksar (OPVM, 2014a; OPVM, 2014b).	The establishment of an eco-park in Tafilelt is aimed at enhancing the overall quality of life in the area (Tafilelt, n.d.-b).
Buildings height	Maximum height: 7.5 m (OPVM, n.d.-c).	maximum height: 9 m
Structuring elements	The mosque, the market, the fortification wall, cemeteries, urban entrances, and wells (OPVM, 2015).	the fortification wall, urban entrances, and eco-park
Legal and administrative situation	Since 1982, the M'zab Valley has been included in the List of World Heritage Sites of UNESCO (OPVM, 2012b).	Classified ecological village (APS, 2021)
House design	The house is an introverted, hierarchical (going from public to private), and versatile space designed around the central patio (OPVM, 2015).	Introverted shape, with few openings to the outside
Construction materials	Stone, lime, Timchemt (local or traditional plaster consisting of calcium sulfate dihydrate with a chemical formula of $CaSO_4 \times 2H_2O$), clay, tree trunks, or palm trees (OPVM, n.d.-d; Chaib and Kriker 2022).	Stone, plaster, lime, cement, reinforced concrete, brick, cement blocks, and hollow blocks (Gueliane, 2014)
Total ground floor area (dwellings)	ff 100 m² (Gueliane, 2017).	There are 3 models: 60 m², 96 m², and 130 m² (Gueliane, 2014).
Number of floors in buildings	Ground floor, first floor, accessible terrace (OPVM, 2014a)	Ground floor, first floor/second floor, accessible terrace
Patio (the inner courtyard)	The semi-covered patio is located in the center of the house and features a zenithal opening known as a "chebek". This variable-width opening improves ventilation and natural lighting (Gueliane, 2017).	The patio is located in the center of the house and features a zenithal opening known as a "chebek".
Skiffa, or (entrance in chicane)	A space is adjacent to the entrance door that separates the interior of the dwelling from the outside, adding to privacy, obscuring and concealing the interior space, contributing to the natural illumination of the dwelling, and improving ventilation (OPVM, 2014b).	This architectural element, inspired by the dwellings of Ksar Beni Isguen, has been incorporated into the modern designs of houses in Ksar Tafilelt with certain modifications.
Chebek	"Chebbek" is a central zenithal opening with an area of about 2 m², covered with a metallic grille that allows light, natural ventilation, and heat regulation (OPVM, 2014b; Gueliane, 2017).	"Wast-eddar", which is the center of the dwelling, and "chebek", which are repeated in a stacked arrangement, are found on both the ground floor and the house's first floor. At the terrace level, there is a glazing structure that encloses the chebek specifically.
Courtyard	The use of an interior courtyard is rare in the region's traditional dwellings.	The courtyard has been used in the dwellings of Ksar Tafilelt as one of the most important passive environmental strategies in arid regions.
Openings	A small number of openings and small sizes characterize the facades of traditional dwellings in the Ghardaïa region. They are often located only on the first floor (OPVM, 2014b).	The windows are larger. These windows are typically crafted from wood and feature the distinctive Mashrabiya architectural element.
Colors	While painting the exterior facades of the houses, colors standard in nature are used, with light colors that help prevent heat absorption and reflect sunlight (OPVM, n.d.-c; Gueliane, 2017; Bensayah, Bencheikh and Abdessemed, 2019).	The color strategy implemented in Ksar Beni Isguen was also employed in Ksar Tafilelt.
Passive strategies	Local materials, load-bearing stone walls, the terrace, the gallery, the patio, Chebek, Skifa (entrance in chicane), and blind facade.	local materials, load-bearing stone walls, the courtyard, the patio, chebek, Mashrabiya, the terrace, and skifa (entrance in chicane).

Furthermore, this information was meticulously organized and structured into an analytical framework, denoted as Table IV. The objective of this analytical framework was to facilitate a comparative assessment of the strategies and solutions found in contemporary architecture within the Ksar-Tafilelt area. The institution in charge of the project was the one driving this effort, which sought to draw inspiration from M'zab's vernacular architecture. In doing so, this institution sought to reconcile traditional architectural practices with the contemporary requirements of modern living.

Case Studies

• **Dwelling 1: Located in the Ksar Beni Isguen Region** – The selected residential structure for the simulation (Fig. 4) is situated in the western sector of Ksar Beni Isguen, conforming to the architectural conventions of the vernacular style. Its footprint encompasses a total built-up area spanning 90 m², while the overall building area extends to 142.62 m². This dwelling comprises a ground floor, a first floor, and an accessible upper terrace designated for summer-night sleeping. The fundamental architectural framework of this residence relies upon load-bearing stone walls, some of which attain a thickness of approximately one meter on the ground level, gradually diminishing in thickness as they ascend. This specific wall construction greatly augments the thermal mass of the structure, thereby influencing the rate of heat transfer. Typically, these walls consist of two or more tiers of stones held together by lime mortar, with the remaining interstices filled with gravel (OPVM, 2012a).

Traditional vernacular dwellings are capped with roofs crafted from locally available natural materials. In this case, dry palm trunks are directly positioned atop the load-bearing stone walls. There are successive layers of perpendicularly oriented palm branches, then a sizable stratum made up of a mixture of small stones and plaster, then a layer of clay. To safeguard the roof against moisture ingress and rainwater infiltration, it is enveloped entirely in a waterproof layer of white lime mortar (OPVM, 2013b).

The walls of this dwelling exhibit a remarkable finish executed entirely with lime mortar, a naturally occurring substance endowed with various advantageous characteristics. Notably, it enables the walls to respire, mitigating excess moisture and providing a healthier indoor environment. Furthermore, the lime material has insulating properties, ensuring the comfort of the occupants regardless of external environmental factors such as noise and temperature fluctuations (OPVM, 2013a).

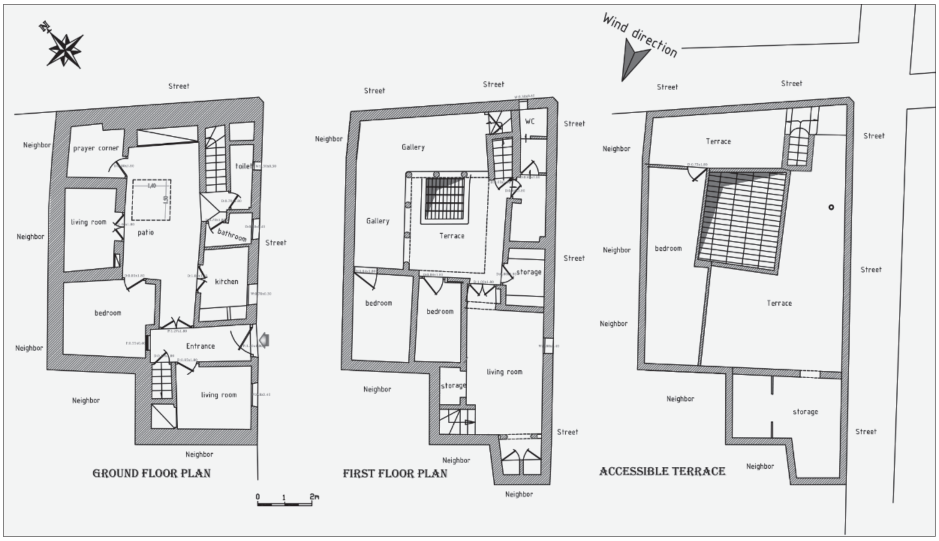


Fig. 4 Architectural plans (dwelling ksar Beni Isguen)

Table V, sets the characteristics of the main simulation building provided by Designbuilder software, which are compatible with the values applied nationally in Algeria.

• **Dwelling 2: Located in Ksar Tafilelt** – The dwelling that was chosen for the modern case study (Fig. 5) is located in the southern part of Ksar Tafilelt. Its interior spaces and construction techniques were inspired by the traditional dwellings in Ksar Beni Isguen, extending over a floor area of 90 m² and a total building area of 142,62 m². It consists of a ground floor, a first floor, and an accessible terrace adjoining the laundry room.

This construction project has used regionally available natural building resources for affordability while ensuring durability and robustness for an extended period. The entire structure is fabricated using stones, lime plaster, and cement materials coupled with reinforced concrete technologies. Concrete pillars and beams support the structure system, which has load-bearing stone walls of 40 cm thickness. The roof is constructed using concrete pillars as support for the solid structure, including reinforced concrete beams and a durable compression slab, which are positioned some 0.65 cm apart from one another. Furthermore, independent plaster moldings have been included in the roof to improve the thermal insulation properties.

Wall cladding in this area continues to implement traditional methods using lime mortar. The preferred approach caters well to the climate conditions in the region, with the features of preventing heat transfer and sound insulation properties. Table VI sets the main simulation building's characteristics, given by Designbuilder software, in accordance with Algeria's national standards.

Table V The materials characteristics of the vernacular dwelling

Designation	Thickness [m]	U-Value [W/m2-K]
External wall (stones, lime mortar, lime)	0,40-1,00	1,625
Internal wall (stone, lime mortar, plaster)	0,20-0,40	2,929
External floor (stones, lime mortar)	0,20	0,251
Floor (stones, lime mortar, sand)	0,20	3,100
Flat roof (lime mortar, layer of clay, stone and plaster mortar, palm branch, palm trunk)	0,20-0,30	1,250
Windows (local wood frame with single glazing)	0,07	5,778
Exterior door (palm wood)	0,10	2,995

Fig. 5 Architectural plans (dwelling ksar Tafilelt)

Table VI The materials characteristics of the Modern dwelling

Designation	Thickness [m]	U-Value [W/m2-K]
External wall (stones, lime mortar, cement, lime)	0,40	4,185
Internal wall (hollow blocks, lime mortar, cement, plaster)	0,20-0,40	2,929
Floor (floor tile, mortar, slab)	0,20	3,350
Flat roof (insulator, slab, mortar, plaster)	0,20	2,780
Windows (wood frame with single glazing)	0,07	1,960
Exterior door (metal door)	0,07	2,003

Results

- **Site and source energy** – As previously stated, both vernacular and contemporary buildings, adhering to the specifications delineated in the preceding section, were modelled within the Design Builder software (Figs. 6 and 7). Subsequently, their energy consumption profiles were assessed over the course of an entire year. This comprehensive annual thermal performance analysis, as elucidated in Table VII, has brought to light the significant distinctions in the energy demand of the two architectural paradigms.

The results reveal significant disparities in energy consumption between vernacular architecture in Ksar Beni Isguen and contemporary residences in Ksar Tafilelt. Specifically, the dwelling in Ksar Beni Isguen consumed a total site energy of 12463.41 kWh, while the contemporary residence in Ksar Tafilelt consumed 30067.04 kWh. Table VII provides a comprehensive overview of the energy consumption parameters for both buildings, which were calculated by Design-Builder software.

It is noteworthy that the contemporary residence in Ksar Tafilelt demonstrated suboptimal energy performance. Its significantly higher figures for overall site energy consumption, total source energy consumption, and energy utilization per unit area of the building›s total footprint stand in stark contrast to the chosen residence in Ksar Beni Isguen. These findings highlight the superior energy efficiency of vernacular architecture, with the dwelling in Ksar Beni Isguen serving as an example.

- **End uses** – To conduct a more precise analysis regarding the reduced energy demand of traditional buildings in comparison to their modern counterparts, a detailed examination of specific energy-consuming components is imperative. Table VIII delineates the energy end-uses in heating and cooling for both types of dwellings, revealing a substantial disparity in cooling demand, quantified at 2452.49 kWh, and heating demand, measured at 10798.89 kWh. Notably, the variation in heating load significantly outweighs that of cooling load, a phenomenon attributed to discrepancies in the external wall structures.

- **Construction** – In vernacular constructions, the thermal conductivity coefficient (U-Value) of external walls stands at 1.680 (W/m²-K) watts per square meter – degrees Kelvin, while the roof exhibits a coefficient of 1.25 (W/m2-K). Conversely, modern buildings feature notably higher coefficients, specifically 4.57 (W/m²-K) for external walls and 2.80 (W/m²-K) for the roof. This pronounced contrast underscores the pivotal role of structural composition, especially the thermal conductivity coefficients of external walls and roofs, in dictating the distinct energy demands between traditional and modern architectural designs. Such intricate analysis provides invaluable insights into the nuanced factors shaping energy efficiency in diverse building types.

- **Gross Wall Area and Window-to-Wall Ratio** – In comparing the designs of the two buildings, a significant disparity lies in the Gross Wall Area (GWA) and the Window-to-Wall Ratio (WWR) across different facades. It is imperative to note that, excluding variables pertaining to geometry, materials, and WWR, a precise evaluation of these factors' impact on energy consumption necessitates the fixation of parameters such as lighting, HVAC, and zone activity for both cases.

Table VII The total site energy and total source energy of two selected buildings

	Dwelling Ksar Beni Isguen		Dwelling Ksar Tafilelt	
Indicators	Total energy [kWh]	Energy per total building area [kWh/m²]	Total energy [kWh]	Energy per total building area [kWh/m²]
Total site energy	12463.41	77.76	30067.04	167.05
Total source energy	32417.80	202.27	88742.57	493.05

Table VIII The energy end-uses in heating and cooling for both types of dwellings

	Dwelling Ksar Beni Isguen		Dwelling Ksar Tafilelt	
Indicators	Electricity [kWh]	Natural gas [kWh]	Electricity [kWh]	Natural gas [kWh]
Heating	0,00	5747.62	0,00	16546.51
Cooling	4773.51	0,00	7226.00	0,00

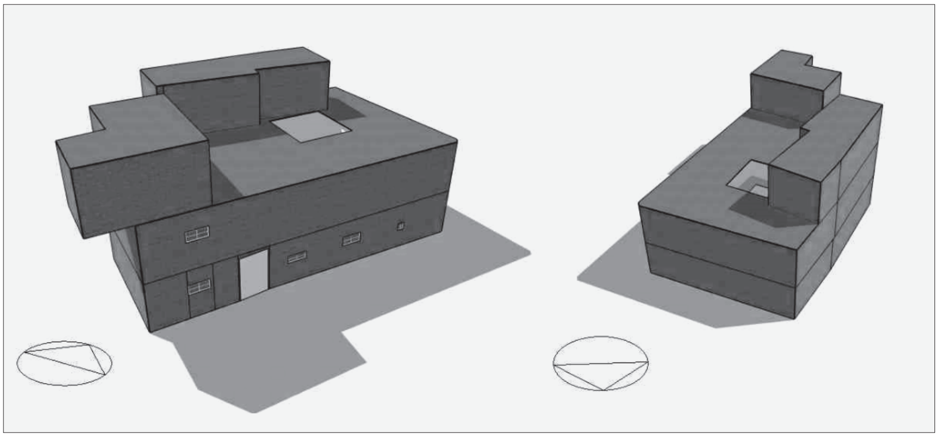
Analyzing the Gross Wall Area (GWA) as outlined in (Table IX), observations reveal noteworthy distinctions between the vernacular and modern houses. Specifically, the GWA of the wall on the northern front of the vernacular house is 7% smaller than that of the modern house. This reduction amplifies to 15% on the southern front. Similarly, on the eastern and western fronts, the vernacular house exhibits GWA reductions of 6.6% and 13.5%, respectively, in comparison to the modern house. In summation, the total GWA of the wall in the vernacular house is 11% less than that of the modern house.

This disparity in Gross Wall Area signifies that the surface area of the wall exposed to external air in the vernacular house (Dwelling Ksar Beni Isguen) is notably lower than in the modern house (Dwelling Ksar Tafilelt). Consequently, this reduction curtails air exchange and diminishes heat transfer from inside to outside, thereby augmenting energy consumption efficiency.

Conversely, data from (Tables IX and X) underscores that the opening surface area in the external walls of a modern house surpasses that of a traditional house. This differential area of openings increases heat exchange between the interior and exterior of a modern house in comparison to a vernacular house. Specifically, the opening area in the external walls of the modern house exceeds that of the vernacular house by 317%.

Therefore, it can be understood that the Gross Wall Area and Window-to-Wall Ratio influence energy consumption efficiency. The observed variations emphasize the importance of considering these factors comprehensively in architectural design to optimize energy efficiency and sustainability.

• **Comfort PMV** – Assessing the comfort of individuals in different settings is a task that involves considering factors such as their personal thermal balance and the microclimate of the space. To determine how people are likely to feel in specific conditions, a thermal sensation scale ranging from -3 to +3 is used, along with calculations based on indices like PMV (predicted mean vote) and PPD (percentage of people dissatisfied) (Velt and Daanen, 2017). PMV and PPD indices are based on studying how humans feel in controlled environments and provide measurements of comfort. These indices play a role in the ISO 7730 standard (ISO 7730, 2005), which utilizes a seven-level scale to assess sensation as shown in Table XI and quantifies thermal comfort using PMV and PPD percentages (Laouadi, 2022). PMV is a measure of how warm or cool people feel on average, while PPD tells us the percentage of individuals who're not satisfied with the room's conditions. PMV considers factors that affect in-



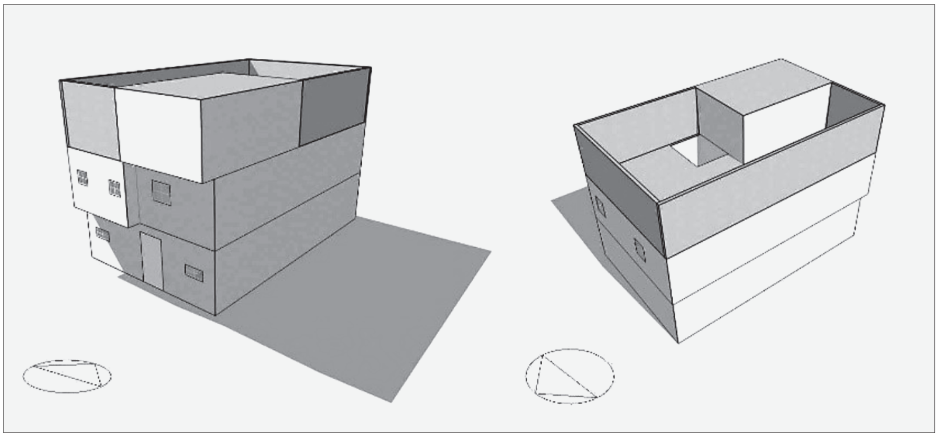


Fig. 6 Design Builder modelling of the vernacular building
Fig. 7 Design Builder modelling of the contemporary building

Table IX Gross wall area and Window-to-Wall Ratio (Dwelling Ksar Beni Isguen)

	Total	North (315 to 45°)	East (45 to 135°)	South (135 to 225°)	West (225 to 315°)
Gross Wall Area [m²]	240.10	47.74	76.98	44.04	71.34
Above Ground Wall Area [m²]	240.10	47.74	76.98	44.04	71.34
Window Opening Area [m²]	1.18	0.00	1.18	0.00	0.00
Gross Window-to-Wall Ratio [%]	0.49	0.00	1.53	0.00	0.00
Above Ground Window-to-Wall Ratio [%]	0.49	0.00	1.53	0.00	0.00

Table X Gross wall area and Window-to-Wall Ratio (Dwelling Ksar Beni Tafilelt)

	Total	North (315 to 45°)	East (45 to 135°)	South (135 to 225°)	West (225 to 315°)
Gross Wall Area [m²]	267.66	51.38	82.45	51.38	82.45
Above Ground Wall Area [m²]	267.66	51.38	82.45	51.38	82.45
Window Opening Area [m²]	3.75	1.43	0.00	2.31	0.00
Gross Window-to-Wall Ratio [%]	1.40	2.79	0.00	4.50	0.00
Above Ground Window-to-Wall Ratio [%]	1.40	2.79	0.00	4.50	0.00

TABLE XI THERMAL SENSATION SCALE

Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
-3	-2	-1	0	+1	+2	+3

TABLE XII COMFORT INDICATORS

Indicators /(year)	Dwelling Ksar Beni Isguen	Dwelling Ksar Beni Tafilelt
Air Temperature (ºC)	22.40	21.75
Radiant Temperature (ºC)	22.56	21.32
Operative Temperature (ºC)	22.48	21.54
Outside Dry-Bulb Temperature (ºC)	17.68	17.68
Relative Humidity (%)	56.20	56.54
Fanger PPD (%)	21.15	47.33
Discomfort hrs (all clothing) (hrs)	1544.47	1582.32
Fanger PMV	-0.27	-1.28

dividuals and their environment using the concept of operative temperature, which combines the weighted average of air temperature and mean radiant temperature (Cichowicz and Stelęgowski, 2018).

The ideal level of comfort is considered to be between -0.5 and +0.5 on the PMV scale (ISO 7730, 2005). If the PMV values go beyond +2 or drop below -2, it indicates conditions that can negatively affect the well-being of occupants (Cichowicz and Stelęgowski, 2018).

In the context of this study, the thermal comfort criteria proposed by Fangar were applied to assess the interior conditions of both traditional and contemporary dwellings. The findings revealed a PMV value of -1.28 for the modern house and -0.27 for the native house. As indicated in Table XII, the thermal comfort conditions in the native house markedly surpass those in the modern house.

DISCUSSION

The comparative analysis of traditional vernacular architecture in Ksar Beni Isguen and contemporary construction in Ksar Tafilelt offers profound insights into the intricate relationship between architectural design, energy efficiency, and human thermal comfort. This extended discussion delves deeper into the nuanced aspects of each parameter, providing a comprehensive understanding of the findings.

- **Architectural characteristics and thermal performance** – Vernacular architecture in Ksar Beni Isguen is characterized by its ingenious use of local materials and traditional construction techniques, resulting in superior thermal performance. The load-bearing stone walls, some reaching a thickness of one meter, act as a substantial thermal mass, moderating temperature fluctuations within the dwelling. The lime mortar used in construction not only binds the stones together but also possesses excellent insulating properties, contributing to the structure's energy efficiency. Additionally, the roofing system, crafted from dry palm trunks and branches, provides natural insulation and minimizes heat ingress. These indigenous construction practices highlight the symbiotic relationship between architecture and the environment, utilizing available resources to create energy-efficient habitats. In contrast, the contemporary dwelling in Ksar Tafilelt incorporates modern construction materials, including reinforced concrete and cement. While these materials offer structural strength, they lack the natural insulating properties of traditional components. The absence of an adequate thermal mass in the contemporary structure results in rapid heat transfer, leading to increased energy consumption for temperature regulation. Although attempts have been made to enhance insulation, as evidenced by the use of independent plaster moldings in the roof, they fall short of replicating the thermal efficiency achieved by vernacular construction methods.

- **Energy efficiency** – The energy consumption analysis provides compelling evidence of the energy-saving potential inherent in vernacular architecture. The traditional dwelling in Ksar Beni Isguen consumes significantly less energy (12463.41 kWh) compared to the contemporary residence in Ksar Tafilelt (30067.04 kWh) over the course of a year. This substantial difference underscores the importance of architectural design and construction materials in minimizing energy demands. The higher energy consumption in a modern house can be attributed to several factors, including higher thermal conductivity coefficients of the external walls and roof, larger window-to-wall ratios, and the absence of a substantial thermal mass.

The thermal conductivity coefficients (U-Values) of external walls and roofs play a pivotal role in determining the energy efficiency of buildings. In vernacular constructions, the U-Value of external walls is 1.680 W/m²-K, and the roof exhibits a coefficient of 1.25 W/m²-K. These values indicate efficient insulation properties, resulting in reduced heat transfer between the interior and exterior environments. Conversely, the contemporary building features significantly higher U-Values of 4.57 W/m²-K for external walls and 2.80 W/m²-K for the roof. These elevated coefficients mean increased heat exchange, necessitating higher energy consumption for climate control.

- **Gross Wall Area and Window-to-Wall Ratio** – The architectural design of buildings significantly impacts their energy consumption patterns. The Gross Wall Area (GWA) and Window-to-Wall Ratio (WWR) are crucial parameters influencing heat exchange and natural lighting within structures. A meticulous analysis of these factors in both dwellings sheds light on their implications for energy efficiency.

The vernacular house in Ksar Beni Isguen exhibits a smaller GWA and lower WWR than the modern house in Ksar Tafilelt. The GWA reductions, varying from 6.6% to 15% across different facades, result in a notable decrease in the surface area exposed to external air. This reduction curtails air exchange and diminishes heat transfer, contributing to energy consumption efficiency. The smaller openings in the external walls of the vernacular house restrict heat loss during colder periods and heat gain during warmer seasons, enhancing overall thermal performance.

Conversely, the modern house features larger openings, leading to a 317% increase in the opening area in external walls compared to the vernacular house. While these openings provide ample natural light, they also facilitate increased heat exchange between the interior and exterior. This heightened heat transfer necessitates greater energy consumption for heating and cooling purposes, adversely impacting the building's overall energy efficiency.

- **Human thermal comfort** is a multifaceted aspect influenced by individual physiological factors, clothing, metabolic rate, and environmental conditions. Evaluating thermal comfort within indoor environments necessitates comprehensive analysis, considering various indices and scales. In this study, the Predicted Mean Vote (PMV) scale was employed, providing valuable insights into the occupants' thermal sensations.

The PMV scale, ranging from -3 to +3, allows for an evaluation of thermal comfort. It's important to consider the subtle aspects. The ideal level of comfort can vary depending on preferences and environmental factors; it is located within the range of -0.5 ⇠ PMV ⇠ +0.5, indicating a neutral sensation. PMV values exceeding +2 or falling below -2 signify extreme microclimatic conditions detrimental to occupants' well-being. The evaluation of thermal comfort in both dwellings revealed a PMV value of -1.28 for the modern house and 0.27 for the vernacular house. These values indicate a more favorable thermal environment in the vernacular dwelling, aligning with the lower energy consumption observed.

The dynamic adaptation of PMV across different months, as illustrated in the graph, provides valuable insights into the temporal variations of thermal comfort. Seasonal fluctuations, influenced by external climate conditions, necessitate adaptive architectural strategies to maintain consistent thermal comfort year round. The vernacular house's ability to sustain a more stable thermal environment can be attributed to its superior insulation properties and reduced heat exchange with the exterior, as evidenced by the smaller GWA and lower WWR.

- **Implications for sustainable architecture** – The findings of this study have significant implications for sustainable architecture and construction practices. Traditional vernacular architecture, rooted in indigenous knowledge and adapted to local environmental conditions, offers valuable lessons for contemporary architects and builders. The integration of natural materials, strategic architectural design, and optimized GWA and WWR can substantially enhance energy efficiency and occupant comfort.

In the context of sustainable architecture, the study underscores the importance of embracing eco-friendly materials and energy-efficient design principles. Natural materials such as stone, lime mortar, and palm wood not only contribute to energy efficiency but also reduce the environmental impact associated with modern construction materials. Furthermore, indigenous construction techniques, honed over generations, exemplify sustainable practices that prioritize both human comfort and environmental conservation.

- **Limitations and future research** – While this study provides a comprehensive analysis of traditional and contemporary dwellings, certain limitations should be acknowledged. The analysis focuses primarily on thermal performance and energy consumption, overlooking other aspects such as embodied energy, life cycle analysis, and economic considerations. Future research endeavours could encompass a holistic evaluation of sustainable architecture, encompassing a broader spectrum of parameters to provide a more nuanced understanding of the subject.

Additionally, further studies could explore the potential integration of modern technologies and materials with traditional architectural principles. Hybrid approaches, blending the wisdom of vernacular construction with innovative solutions, could pave the way for the development of highly efficient and sustainable buildings. Collaborative efforts between architects, engineers, and local communities can facilitate the exchange of knowledge, fostering the evolution of sustainable architectural practices.

Conclusion

In conclusion, this study elucidates the significant advantages of traditional vernacular architecture in promoting energy efficiency and human thermal comfort. The utilization of natural materials, strategic architectural design, and careful consideration of factors like Gross Wall Area and Window-to-Wall Ratio contribute to the superior performance of traditional dwellings. These findings underscore the importance of integrating indigenous architectural knowledge and sustainable building practices into modern construction to enhance the efficiency of energy utilization, increase the comfort of those occupying the space, and increase overall sustainability. Future architectural endeavours should draw inspiration from these insights to create environmentally responsible and comfortable living spaces.

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Abbreviations

PMV – Predicted Mean Vote
PPD – Predicted Percentage of Dissatisfied
ASHRAE – American Society of Heating, Refrigerating, and Air-Conditioning Engineer
OPVM – Office of the Protection and the Promotion of the M'ZAB Valley
MAEM – Algerian Ministry of Energy and Minerals

Sources of illustrations and tables

Fig. 1	Bing Maps, adapted by the authors, 2023
Fig. 2	Wikipedia, adapted by the authors, 2023
Fig. 3	climatestotravel.com, adapted by the authors, 2023
Figs. 4-7	Authors
Tables I-X, XII	Authors, 2023
Table XI	Laouadi, 2022

Authors' biographies and contributions

Abdelwahab Messaitfa is a Ph.D. student in architecture at the University of Constantine 3, Algeria, specializing in architectural and urban heritage and landscapes.
Professor **Meriama Bencherif** supervises his academic research. Both actively contribute to the Laboratory of Urbanism and Environment at the same university. The laboratory is renowned for its extensive scientific publications in architecture, urbanism, and the environment.

Conceptualization: A.M and M.B.; methodology: A.B. and M.B.; software: A.M.; validation: A.B. and M.B.; formal analysis: A.B. and M.B.; investigation: A.M.; resources: A.M.; data curation: A.M.; writing – original draft preparation: A.M.; writing – review and editing: A.B. and M.B.; visualization: A.M.; supervision: M.B.; project administration: A.M.; funding acquisition: A.M.