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Sustainable Dwelling Design Principles in Libya: Strategies for Eco-Friendly Architecture

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Abstract

This study explores how Libyan building construction incorporates environmental design principles for energy efficiency and sustainability. Libya struggles with sustainable development due to its fossil fuel dependence, water scarcity, and extreme weather patterns. Traditional Libyan architecture, such as that found in Ghadames, has used passive cooling and sustainable design, but modern construction relies on energy-intensive mechanical systems, increasing consumption and environmental impact. This research examines architectural methods to improve energy efficiency, thermal comfort, and building sustainability in Libya's hot and arid climate. The methodology consists of a comprehensive literature review and an analysis of two case studies: traditional dwellings in Ghadames and a sustainable international building in Saudi Arabia selected for its similar climate to Libya. The case studies were assessed based on energy usage, thermal performance, and sustainability. The findings indicate that traditional architecture in Ghadames, with its passive cooling techniques, thick walls, and use of locally available materials, provides superior thermal comfort and energy efficiency compared to modern buildings. The international case study demonstrates how renewable energy systems and advanced sustainable design techniques can be integrated to enhance energy efficiency and sustainability. The study emphasizes the advantages of adopting sustainable building design practices in Libya. Embracing sustainable practices not only conserves energy and reduces carbon emissions, but also improves occupant comfort and supports sustainable development. The research highlights the need for modern Libyan architecture to incorporate traditional design principles into contemporary technologies to address environmental challenges effectively.

Keywords: Sustainable Architecture, Energy Efficiency, Passive Cooling, Renewable Energy, Traditional Libyan architecture

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مبادئ تصميم المساكن المستدامة في ليبيا: استراتيجيات العمارة الصديقة للبيئة.

روان أنور الواعر، لمياء مصطفى عبد ربُ

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الملخص

تستعرض هذه الدراسة كيف يمكن أن تدمج المنازل الليبية مبادئ التصميم البيئي لتحقيق الكفاءة في استهلاك الطاقة والاستدامة. تواجه ليبيا تحديات كبيرة في مجال التنمية المستدامة بسبب الاعتماد على الوقود الأحفوري، ندرة المياه، والظروف الجوية القاسية. في حين أن العمارة التقليدية الليبية، مثل تلك الموجودة في غدامس، استخدمت أساليب التبريد السلبي والتصميم المستدام، فإن المنازل الحديثة تعتمد على أنظمة ميكانيكية عالية الاستهلاك للطاقة، مما يزيد من الاستهلاك والأثر البيئي. لذا، تركز هذه الدراسة على استكشاف الأساليب المعمارية لتحسين كفاءة الطاقة وراحة الحرارة واستدامة المباني في مناخ ليبيا الحار والجاف. تشمل المنهجية مراجعة شاملة للأدبيات وتحليل مقارن لحالتين دراسيتين: المساكن التقليدية في غدامس وبناية دولية مستدامة في المملكة العربية السعودية. تم تقييم حالات الدراسة من حيث استهلاك الطاقة، أداء الحرارة، والاستدامة. تشير النتائج الرئيسية إلى أن العمارة التقليدية في غدامس، مع تبريدها السلبي، جدرانها السميكة، واستخدامها للمواد المحلية المتاحة، توفر راحة حرارية وكفاءة طاقية أفضل من البناءات الحديثة. تُظهر دراسة الحالة الدولية كيف يمكن لأنظمة الطاقة المتجددة والتصميم المستدام المتقدم أن تعمل معًا. تؤكد الاستنتاجات على مزايا اعتماد نهج صديق للبيئة في تصميم المباني في ليبيا. إن تبني الممارسات المستدامة يحافظ على الطاقة ويقلل من انبعاثات الكربون، كما يحسن راحة السكان ويدعم التنمية المستدامة. تسلط الدراسة الضوء على الحاجة إلى دمج مبادئ التصميم التقليدي مع التكنولوجيا المعاصرة في العمارة الليبية الحديثة لمواجهة التحديات البيئية بفعالية.

الكلمات المفتاحية: العمارة المستدامة، كفاءة الطاقة، التبريد السلبي، الطاقة المتجددة، العمارة التقليدية الليبية.

1. Introduction

In recent years, the world's attention has increasingly focused on energy efficiency and environmental sustainability, especially in the building industry, which is responsible for 50% of global energy consumption and 50% of greenhouse gas emissions [1], Libya faces unique challenges due to its arid climate. Traditional architecture, such as that found in Ghadames, has historically employed passive cooling techniques and sustainable design principles to address these challenges. In contrast, modern construction often relies on energy-intensive mechanical systems, leading to increased energy consumption and environmental degradation. Research demonstrates that passive design strategies effectively reduce energy consumption, and projects incorporating renewable energy and eco-friendly principles yield significant benefits. However, there is a lack of implementation of sustainable design principles in Libya, as contemporary architecture often overlooks local climate considerations and renewable energy potential. This

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research aims to explore and evaluate architectural strategies that enhance energy efficiency, improve thermal comfort, and reduce the ecological footprint of buildings in Libya. The research addresses the following key questions: How can historic Libyan architecture be integrated with current technology to support sustainable building practices? What advantages do passive cooling methods offer over modern mechanical systems? How might the use of local materials improve building performance?

By examining traditional methods and integrating them with modern construction technologies, the study aims to develop sustainable architectural design strategies tailored to Libya's climate. This study is significant because it offers useful insights into environmentally-friendly architectural strategies, which contribute to the broader objectives of sustainable development and climate resilience in Libya [2].

2. Methodology

This research employs a detailed methodology combining a literature review with case study analysis to explore sustainable design principles for enhancing energy efficiency and environmental performance in Libyan architecture. The methodology is structured in the following manner:

- **Literature Review**: The study explores sustainable design principles, focusing on passive and active cooling techniques, energy efficiency, and renewable energy systems, providing a theoretical framework for understanding their effectiveness in arid climates like Libya.

- **Software Tools Used:** Revit for recreating a 3D model, Insight 360 for energy simulation of thermal performance and energy consumption, and Green Building Studio for analyzing energy use intensity (EUI) and carbon emissions.

- **Case Studies Analysis**: The study analyzes traditional dwellings in Ghadames, Libya, and a modern sustainable building in Saudi Arabia, focusing on their relevance and climate conditions, highlighting similarities in their design.

The traditional dwellings in Ghadames exemplify passive cooling techniques and sustainable design adapted to harsh desert conditions, providing insights into energy efficiency and thermal comfort. In contrast, the KAUST House in Saudi Arabia represents contemporary sustainable design, integrating advanced technologies and renewable energy systems, achieving LEED Platinum certification. Together, these case studies illustrate effective strategies for sustainable architecture in hot desert climates.

The case studies are evaluated based on energy usage, thermal performance, and sustainability, comparing passive and active design strategies while considering indoor comfort and environmental impacts. The analysis indicates that integrating traditional and modern design principles can enhance energy efficiency and sustainability in Libyan architecture.

Through this methodology, the research aims to provide practical recommendations for enhancing sustainable design practices in Libya, supporting the development of energy-efficient and environmentally responsible buildings.

3. Literature Review

3.1. Background of Sustainability and Housing in Libya

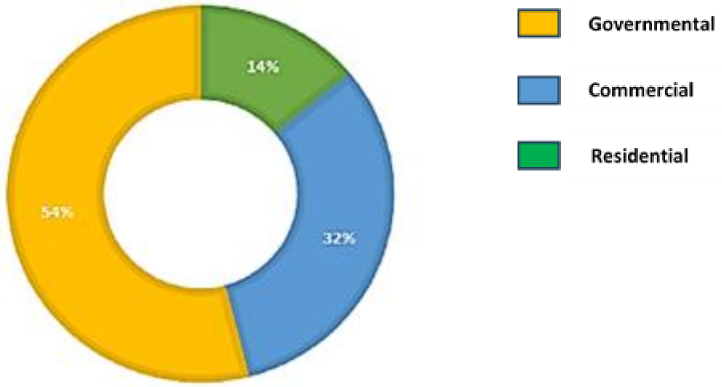

Figure 1: Electricity consumption by sectors in Libya. (Adopted from [8])

Libya faces considerable sustainability challenges due to its reliance on fossil fuels, water scarcity, and rapid urbanization. The energy sector's reliance on nonrenewable resources contributes to a 7% annual rise in greenhouse gas emissions, as well as a significant increase in energy consumption [3]. The arid climate further exacerbates water scarcity, necessitating desalination and the Great Man-Made River Project [4]. The housing sector, crucial for providing safe and affordable dwellings, often prioritizes traditional architectural styles over energy efficiency and sustainability [5]. Traditional homes, typically built with concrete and bricks, have high thermal mass but poor insulation, resulting in substantial heat gain and loss [6]. The residential sector accounts for over a half of the country's energy consumption, with many homes lacking modern energy-efficient features [7]. The limited use of renewable energy sources, such as solar panels, further undermines sustainability [8].

Due to a lack of comprehensive frameworks and education, Libya frequently neglects environmental concerns, leading to low levels of sustainable practices and renewable energy adoption [9], [10]. Electricity consumption by sectors in Libya is illustrated in Figure 1.

3.2. Environmental Challenges Concerning Sustainability Development in Libya

3.2.1. Extreme Temperatures and Solar Radiation

Libya's extreme temperatures, particularly in inland and desert regions where summer highs often exceed 40°C, necessitate effective thermal insulation and natural ventilation to maintain indoor comfort. These measures can reduce cooling energy consumption by up to 30% [8]. However, many Libyan homes lack proper insulation and ventilation, leading to higher electricity demand for air conditioning [11].

Despite these challenges, Libya's abundant solar radiation—up to 7.1 kWh/m² daily and over 3,500 sunlight hours annually—offers immense potential (see Figures 2 & 3). Utilizing less than 5% of the Libyan Desert for solar energy could power all of Europe and supply the energy required for the Great Man-Made River (GMMR) water pumping and desalination without greenhouse gas emissions.

3.2.2. Water Scarcity

Libya, one of the world's driest countries, faces severe water scarcity. The Water Resources Institute ranked it sixth for water stress in 2019, with projections indicating worsening conditions by 2040, posing threats to national water security and economic stability (see Figures 4 & 5) [12]. Libya's renewable water resources are critically low, averaging 287 liters per capita per day, significantly below the World Health Organization's recommended 50-100 liters for basic needs. Libya's per capita water consumption is alarmingly high at 2,392 liters, far exceeding regional and global averages. Agriculture consumes 83.1% of the nation's water, with domestic demand projected to increase by 39.5% between 2010 and 2030 [13].

Libya relies heavily on non-renewable aquifers and desalination, with GMMR providing 6.5 million m³ of freshwater daily to northern cities. Groundwater accounts for over 95% of Libya's water withdrawal, with 5,830 million m³ extracted in 2012.

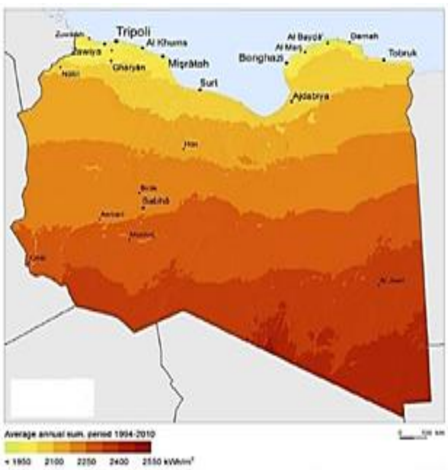

Figure 2: The average radiation on horizontal plan [8].

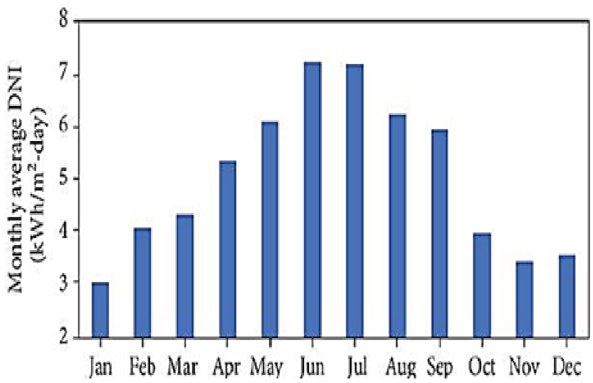

Figure 3: The monthly average global daily solar radiation on horizontal surface.[11]

However, current groundwater withdrawal exceeds sustainable levels, with 3,650 million m³/year being the maximum sustainable limit. The absence of water pricing and overreliance on groundwater have led to wasteful practices and inefficient water distribution, necessitating effective water demand reduction strategies [14].

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3.2.3. Oil Dependency

Libya is heavily dependent on fossil fuels, particularly oil and natural gas, which contribute to global warming and pose environmental and health risks. The combustion of these fuels releases significant amounts of carbon dioxide and pollutants, adversely affecting global climate patterns [15]. Libya is recognizing the importance of sustainable practices despite political instability and infrastructure issues. The National Sustainable

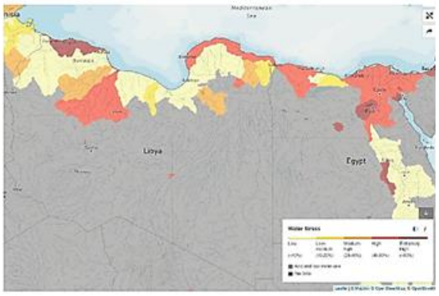

Figure 4: Map of water stress in Libya [12].

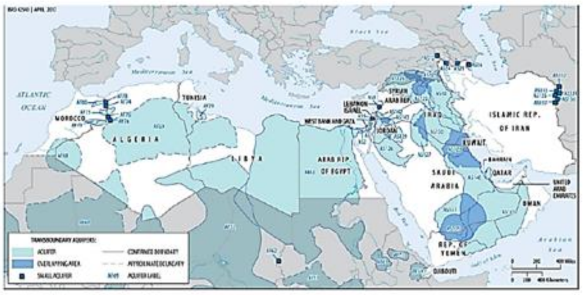

Figure 5: Major transboundary aquifers in MENA region [12].

Energy Strategy, developed by the National Economic and Social Development Board's Electricity and Renewable Energy Committee, aims to improve the electric power and renewable energy sectors by 2035, with a target of generating 20% of electricity from renewable sources by 2030 [4], [12] & [16]. Despite these efforts, Libya continues to rely heavily on fossil fuels for electricity generation. In 2016, Libya ranked 99th globally in electricity consumption, with 99.9% of its electricity derived from, using 28.48 billion kWh (4,680 kWh per capita), and 60th in natural gas consumption, with 3.76 billion m^3 (704.36 m^3 per capita) In 2015, Libya generated 3,105 kilotons of oil equivalent (ktoe) of electricity, with 99.9% derived from fossil fuels [11].

3.2.4. Desertification and Land Degradation:

Agriculture consumes the most water, and domestic demand is rising [10]. The country relies heavily on non-renewable aquifers and desalination, with the Great Man-Made River Project supplying freshwater to northern cities [14].

3.2.5. Dust and sandstorms

Dust and sandstorms can damage building surfaces, necessitating the use of durable materials and air filtration systems to improve air quality.

3.2.6. Sustainable Dwelling Design Principles for Libya

In sustainable design for arid regions, both passive and active systems are crucial for improving energy efficiency and thermal comfort. The following is the Literature Review

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Comprehension Table 1, concentrating on research pertaining to passive and active systems for energy efficiency and the integration of renewable energy.

Table 1: Sustainable Dwelling Design Principles for Libya (2015-2024). Source: The researcher.

Study	Authors	Focus Area	Key Findings	Passive Systems Application	Active Systems Application
Systematic literature review of bioclimatic design elements [18]	Ozarisoy (2021)	Bioclimatic design in Mediterranean climates	Demonstrates the importance of passive cooling tailored to local contexts	Use vernacular passive cooling strategies such as shading devices, natural ventilation, & thermal mass construction in homes	Integrate solar-powered HVAC systems to supplement passive cooling during extreme temperatures
Energy efficiency & building environment [19]	Omer (2016)	Passive and low-energy systems in arid regions	Emphasizes the importance of reducing energy consumption using passive systems	Apply natural ventilation techniques, such as wind towers and shading, to reduce the need for mechanical cooling	Implement solar water heaters and solar cooling systems to reduce energy demands for water heating and air conditioning
Green Material Prospects for Passive Evaporative Cooling Systems [20]	Emdadi (2016)	Use of green materials in passive cooling systems	Explores passive cooling techniques like evaporative cooling using geopolymers	Integrate green materials such as geopolymers and natural insulation to enhance passive cooling	Combine active evaporative cooling units with solar energy to optimize cooling during periods of extreme heat
Energy conservation and renewable technologies for buildings [21]	Ascione (2017)	Energy conservation for passive cooling	Reviews strategies for energy conservation using passive systems such as green roofs, phase change materials & insulation	Use green facades, cool roofs, and thermal mass to passively cool the building envelope	Implement solar chimneys to enhance natural ventilation and photovoltaic panels to generate electricity
Design and thermodynamic analysis of a solar-	Mahmood (2021)	Solar-powered systems for	Explores the use of renewable energy-	Use thermal mass and natural ventilation to maintain	Use solar-powered HVAC systems for cooling and

powered greenhouse for arid climates [22]		**sustainable agriculture in arid climates**	**powered greenhouses in hot climates**	**comfortable indoor conditions in homes**	**heating, and solar-powered desalination systems for water management**
The Potential of Using Passive Cooling Roof Techniques in Arid Regions [23]	Athmani (2022)	**Passive roof cooling techniques**	**Demonstrates that cool roofs significantly reduce indoor temperatures**	**Use cool roof technologies (cool reflective paint, ceramic tiles) to minimize heat gain**	**Integrate solar-powered cooling systems to further reduce energy consumption in residential buildings**
Passive cooling techniques for ventilation: an updated review [23]	**Al-Shamkhe e (2022)**	**Passive ventilation techniques**	**Reviews passive cooling and ventilation techniques for energy-efficient buildings**	**Apply buoyancy-driven ventilation and natural ventilation shafts for air movement**	**Combine solar-powered fans and active cooling systems to enhance airflow and energy efficiency in buildings**

4. Case Studies Analysis

4.1. Ghadames: A Case Study of Ancient Sustainable Architecture in Deserts

Ghadames, known as "The Jewel of the Sahara," is a city in Libya renowned for its unique architecture designed to withstand the harsh desert climate. Situated in an oasis 650 km southwest of Tripoli, Ghadames, located at an elevation of 300-370 meters above sea level, retains warmth during winter nights, benefiting from its unique positioning in the desert [24]. Since 1987, UNESCO has recognized the approximately 800-year-old town of Ghadames as a World Heritage site [25]. The architecture of Ghadames reflects traditional North African desert design, developed to combat the extreme climatic conditions. The summer temperatures often exceed 40°C, while winter days are moderate, and nights can be very cold. The overall climate of the Libyan Desert is dry and hot in summer, with minimal rainfall in winter. Relative humidity ranges from 72% in winter to 17% in summer [26], and the city experiences hot and dusty southerly winds in summer and spring and northerly winds in winter and autumn. Historical data show average minimum temperatures of 2.1°C in January and maximum temperatures of 40.2°C in August, with records exceeding 50°C [27], [28]. The old city of Ghadames specifically designed its settlement pattern and architecture to mitigate the severe summer heat and cold winter nights [29].

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4.1.1. The Characteristics of the City Form

Ghadames is an old city in Libya that showcases desert bio-climate architecture. The city's urban design features covered streets arranged in a compact pattern, with interconnected roofs forming a cohesive urban structure. This design helps to minimize the thermal load on buildings and keeps streets shaded and relatively cool, even on hot days. The narrow gaps between houses allow for cool air circulation and effective ventilation [27], [28], [30] & [31]. The city's traditional architecture has effectively responded to the harsh desert environment by utilizing thoughtful design, construction technology, and materials with specific thermal properties. Surrounding palm farms improve the microclimate by filtering desert winds. Men primarily use the streets, while women complement them with interconnected roof bridges. At 10 meters, the height remains constant. Al-Zubaidi (2002) observed that the design of the streets incorporates frequent, small openings every 15 meters, which create distinct pressure zones. The key design principles include compact urban fabric, covered streets, narrow passageways, exclusive housing designs, and climate-adapted construction materials.

4.1.2. The Characteristics of traditional dwellings in Ghadames

The old city of Ghadames houses consists of four levels, as in Figure 6, with the ground level containing the main entrance, lobby, storage area ventilated by the entrance door, a small sewerage space beneath the toilet, and stairs leading to a toilet positioned between the first and guest area, with access to various bedrooms and storage areas on different levels.

This hall, adorned with brass pots, plaited fabrics, and mirrors that reflect light, stands more than 4 meters high. It incorporates a simple yet effective bio-climatic feature: a small ceiling opening (1 m x 1 m), which facilitates air circulation while preventing external heat from entering. This design ensures a comfortable indoor climate despite external conditions (Figure 7) [30]. The upper level consists of an open terrace with high walls for privacy and air circulation, reserved for women to move between houses via interconnected roofs Figure 10. The kitchen is also located on this floor, providing space for meal preparation and sleeping during summer nights [32], [17].

4.1.3. Building Materials and Construction System

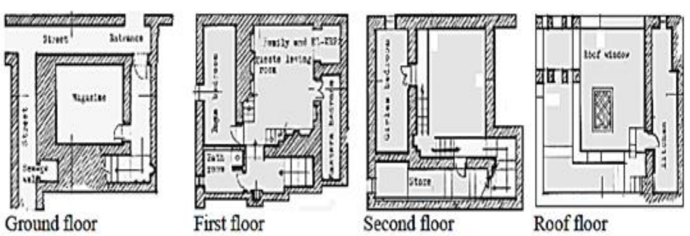

Figure 6: Plans of a typical house in Ghadames [29].

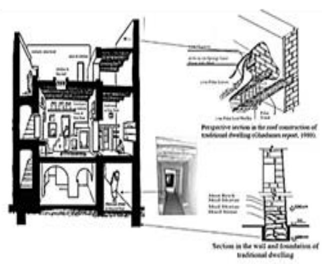

Figure 7: Cross-section of a typical dwelling and Construction Techniques [33].

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Ghadames dwellings are built using locally available materials, such as mud, stone, and hay for thermal resistance. Sun-dried bricks, made from earthy clay mixed with water, are used for walls, with sizes varying according to floor level [30]. According to Daza (1982), sun-dried bricks are the primary material used for walls, with sizes varying according to floor level [29].

The size of the bricks varies by floor level: 0.60 x 0.40 meters on the ground floor, 0.50 x 0.40 meters on the first floor, and 0.40 x 0.40 meters on the top floor [32]. Clay mortar is used to bind bricks, while stone serves as the foundation and sometimes in parapet walls Figure 8. Palm tree wood is used for beams, doors, and shelves, while palm branches are employed to create supporting flooring surfaces. Palm leaves cover these, followed by a mixture of clay, sand, and small stones, and finally, a limestone whitewash Figure 9.

4.1.4. Thermal Performance of Traditional Buildings

To achieve optimal comfort and energy savings in Ghadames, it is important to integrate the design of building form and materials as a cohesive system. This involves

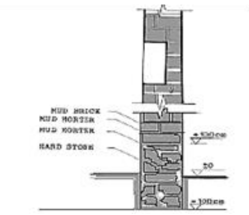

Figure 8: The wall and foundation [27].

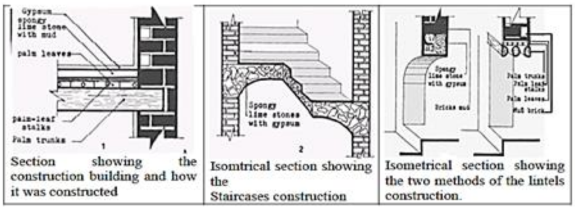

Figure 9: Displays the materials used and techniques employed in constructing buildings [27].

modifying the internal climate of buildings in response to external conditions, with a focus on heat transfer and temperature regulation. The primary climatic factors affecting building interiors in Ghadames are the variation in outside temperatures and extreme solar radiation [32]. Research has shown that traditional houses in Ghadames provide better thermal comfort throughout the year compared to modern buildings [27] and [34].

4.2. Case Study KAUST House, Thuwal, Saudi Arabi

Figure 10: Interconnecting bridges on the roof. Source: Natural Homes. (n.d.). Ghadames, Libya

Figure 11: Celling opining. [27]

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The KAUST House is a model of sustainable residential design in a hot desert climate and has achieved LEED Platinum certification. It integrates traditional and modern techniques by employing passive design strategies as well as advanced material and renewable energy technologies to minimize energy consumption and environmental impact [35]. This case study highlights the house innovation approach to thermal comfort and energy efficiency, offering insight for sustainable housing in similar climates to Libya [36].

4.2.1. Design Strategies

Orientation and Shading: The house is strategically oriented to minimize direct sun exposure while maximizing natural ventilation. Overhangs and shading devices minimize direct sunlight, effectively reducing heat gain [36].

High-Performance Building Envelope: Insulation, reflective roofing, and double-glazed windows help maintain interior temperatures and reduce the cooling load.

Natural Ventilation: The design incorporates cross-ventilation strategies to enhance airflow, reducing reliance on mechanical cooling.

Energy-Efficient Systems: To optimize energy consumption, the house utilizes energy-efficient HVAC systems, LED lighting, and smart home technologies.

Renewable Energy: Installing solar panels helps the house meet its energy needs and lessens its dependency on the grid [35].

Water Efficiency: The house has a greywater treatment system that recycles wastewater for irrigation; a rainwater harvesting tank reduces reliance on municipal water. Low-flow fixtures further enhance efficiency by saving significant water compared to standard fixtures [37].

4.2.2. Thermal Comfort

Figure 12: Solar panels at KAUST smart house.

Figure 13: Ground and first floor.

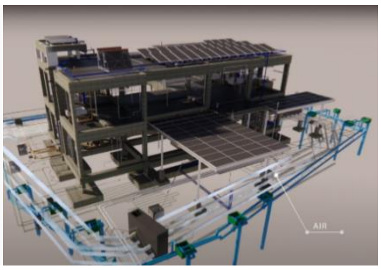

Figure 14: Geothermal and cooling system.

(Source: KAUST Sustainability website)

The KAUST House maintains thermal comfort by regulating the interior temperature between 22°C and 26°C, even when outdoor temperatures exceed 40°C. Advanced HVAC systems achieve this, controlling humidity levels to create a comfortable environment for residents in a desert climate [36].

4.2.3. Energy Performance

The house demonstrates impressive energy performance, achieving a 40% reduction in energy consumption compared to traditional homes in the region [37]. This is due to the solar panels installed on the house which contributes to 30% of the house's energy requirements [33]. As a result of these efficient design strategies and renewable energy integration, the house's annual energy use intensity (EUI) is approximately 80 kWh/m², which is lower than average for similar-sized homes [36], [37].

5. Results

The research explores how integrating environmental design principles into Libyan building construction can improve energy efficiency and sustainability, focusing on fossil fuel dependence, water scarcity, and extreme weather. An exploration of two case studies was undertaken to showcase architectural strategies for managing hot desert climates in a sustainable manner. The traditional Ghadames houses were selected to demonstrate how passive cooling techniques and locally sourced materials provide exceptional thermal comfort and energy efficiency. As detailed in Table 2, Ghadames' compact urban layout and thick-walled dwellings maintain indoor temperatures between 18-25°C, with energy consumption ranging between 40-50 kWh/m²/year.

Table 2: Sustainable Features and Performance Metrics of Traditional Ghadames and Modern KAUST Desert Houses. Source: The researcher.

Feature	Ghadames traditional house	KAUST House, Saudi
Location	Ghadames, Libya	Thuwal, Saudi Arabia
Climate	Hot desert climate with extreme summer heat, cold winter nights	Hot desert climate with extreme summer heat
Building material	Mud, stone, hay, sun-dried bricks, palm wood	Advanced insulation, reflective roofing, double-glazed windows
Thermal performance	Thick walls and compact urban design for thermal regulation	High-performance building envelope, insulation, and reflective roofing
Orientation and shading	Compact form with covered streets, palm trees filtering winds	Strategically oriented with overhangs and shading devices to reduce heat gain
Ventilation	Natural ventilation through narrow streets and small windows roof opening	Cross-ventilation strategies incorporated into the design Energy-efficient HVAC systems
Energy systems	Traditional passive cooling through design and materials	Energy-efficient HVAC systems, LED lighting, smart home technologies
Renewable energy	None	Solar panels contributing 30% of energy needs
Water efficacy	Traditional use of water from oasis, limited modern water efficiency systems	Greywater recycling, rainwater harvesting, and low-flow fixtures
Urban design	Compact, interconnected rooftops for circulation, shaded streets	Modern, individual house design with focus on energy efficiency
Thermal comfort	Maintains 18-25°C indoors despite external temperatures over 40°C	Maintains 22-26°C indoors despite external temperatures over 40°C

Energy use	**Between 40-50 kWh/m²/year**	**Approximately 80 kWh/m²/year**
Energy cost	**9.9 USD/m²/yr**	**5.6 USD/m²/yr**

The second case study, the KAUST House in Saudi Arabia, offers an international example from a comparable desert climate. This LEED Platinum-certified building uses advanced technologies, including a high-performance building envelope, energy-efficient HVAC systems, and solar panels, consuming 80 kWh/m²/year while maintaining indoor temperatures between 22-26°C. The study aims to identify and recommend a blend of passive and active technologies for future sustainable housing in Libya.

The KAUST House is highly water-efficient, incorporating greywater recycling and rainwater collection technologies. Furthermore, the KAUST House has lower energy costs (5.6 USD/m²/yr) compared to modified Ghadames houses (9.9 USD/m²/yr, down from 29.6 USD/m²/yr) as shown in Figure 15.

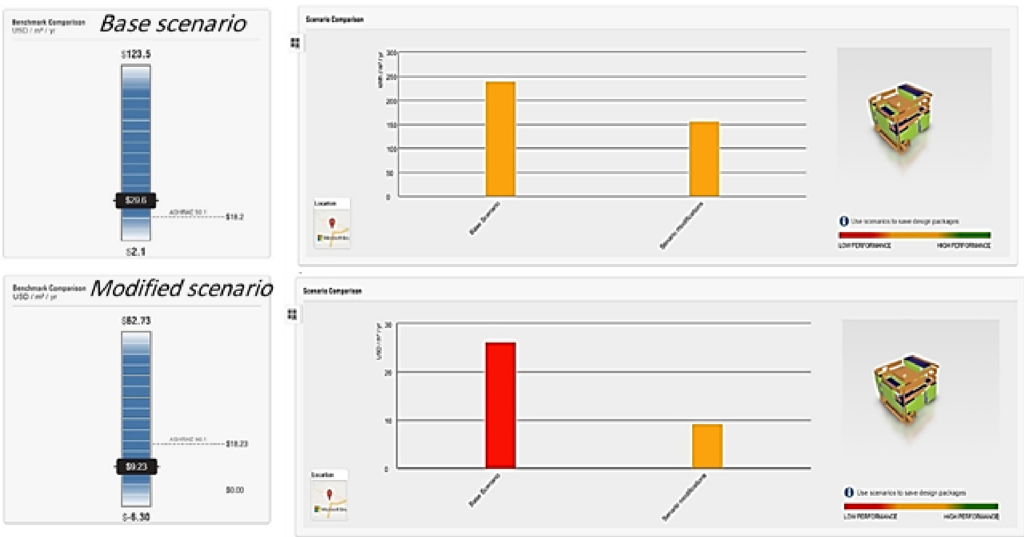

Figure 15: Presents a comparison between the base scenario and the modified scenario, illustrating how the modified scenario achieved ASHRAE 90.1.
Source: The researcher, Software (Revit, Insight 360, Green Building studio).

The charts in Figure 16 illustrate modification factors such as HVAC systems, operating schedules, and PV panel efficiency. They highlight how adjustments in these parameters can influence EUI, providing insights into optimizing energy use in traditional buildings for better sustainability. However, the study concludes that a hybrid approach, combining traditional design with modern sustainable technologies, is essential for achieving energy efficiency, reducing carbon emissions, and improving occupant comfort in Libya's harsh climate.

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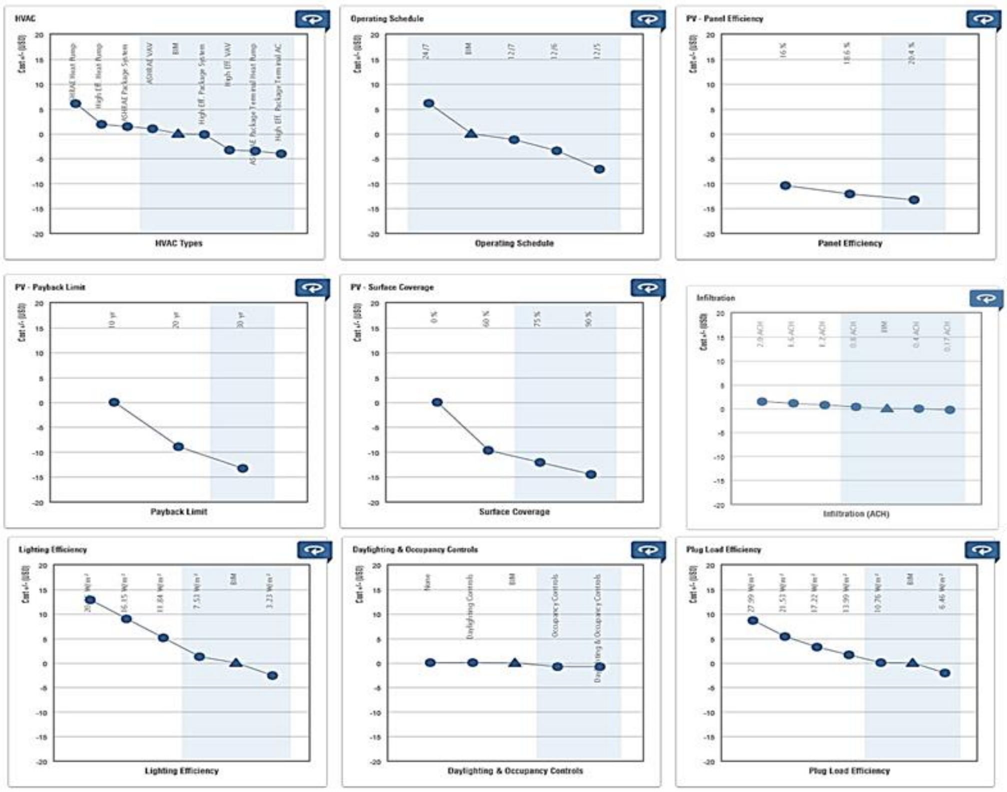

Figure 16: The modification factors like HVAC systems, operating schedules, PV panel efficiency, and more for modified scenario.

Source: The researcher, Software (Revit, Insight 360, Green Building studio).

6. Discussion

6.1. Expected Outcomes

The research aims to demonstrate key findings about the integration of traditional and modern sustainable design principles in Libyan architecture. It is expected to show that passive cooling techniques from traditional Ghadames architecture can significantly improve energy efficiency in residential buildings, reducing reliance on energy-intensive mechanical systems. This integration can result in significantly lower energy consumption and costs by reducing reliance on energy-intensive mechanical systems. The study also predicts that traditional design elements, when combined with modern technologies such as insulation and renewable energy systems, can maintain comfortable indoor temperatures even during extreme weather conditions. The research also highlights the environmental benefits of using locally sourced materials and renewable energy systems, reducing the ecological footprint of buildings. Additionally, the study predicts that adopting sustainable design principles will lead to cost savings over time due to reduced energy consumption and improved resource efficiency. These savings make sustainable building practices more economically viable for widespread adoption in Libya.

6.2. Recommendations

Integrating passive and active systems is essential for developing a sustainable architectural model for Libya. The following hybrid design combines both approaches:

- Passive Cooling: Utilize thick walls, courtyard designs, and shading devices to maintain indoor thermal comfort without relying on mechanical cooling systems.
- Promote Local Materials: Use locally sourced, sustainable materials to enhance environmental sustainability and reduce transportation costs.
- Implement Advanced Insulation: Use high-performance insulation materials and reflective roofing to improve building envelopes and reduce cooling loads.
- Enhance Water Efficiency: Use greywater recycling, rainwater harvesting, and low-flow fixtures to conserve water and improve resource efficiency.
- Active Energy Systems: Install solar PV panels and energy storage systems to sustainably power homes, especially for cooling and lighting needs.
- Smart Integration: Use smart HVAC systems connected to a home energy management system for real-time monitoring and control, optimizing energy use.
- Develop Sustainable Building Codes: Establish mandatory codes for sustainable design principles in new construction projects.
- Increase Public Awareness and Education: Promote sustainable design practices through community engagement and partnerships.
- Encourage Government Support and Incentives: Offer financial incentives and implement policies that encourage sustainable building practices.

7. Conclusion

This research underscores the importance of integrating traditional design principles with modern sustainable technologies to address the environmental challenges of building in hot desert climates such as those in Libya. The traditional architecture of Ghadames demonstrates that passive cooling techniques, local materials, and compact urban designs effectively provide thermal comfort and energy efficiency in harsh climates. However, as illustrated by the KAUST House, incorporating contemporary technologies such as advanced insulation, renewable energy systems, and energy-efficient HVAC significantly enhances these benefits. The findings emphasize the necessity of combining traditional and modern practices in Libyan architecture to achieve energy efficiency and environmental sustainability through a hybrid approach. Adopting these integrated strategies will allow Libya to reduce energy consumption and carbon emissions, while also improving occupant comfort and contributing to sustainable development. The study highlights the critical role that both architectural heritage and innovation play in shaping environmentally sustainable and resilient built environments in arid regions.

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