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Assessing the Experience of Vernacular Environmental Sustainability in Desert Settlements of North African Countries

Ahmed Zaki

ahmed-samir@eru.edu.eg

Egyptian Russian University

Research Article

Keywords: vernacular desert settlements, passive design, environmental sustainability, climate-resilient communities, climate responsive design, Siwa

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RESEARCH

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Abstract

The research attempts to investigate and evaluate the passive strategies applied in urban pattern and building design of vernacular desert settlements in North African countries. The methodology of the research is based on conducting comparative studies among vernacular architecture in different desert regions along North African countries to cover adaptation techniques that are climatic responsive and preserve local environmental and cultural significance. The proposed checklist criteria act as a model for applying and assessing environmental sustainability of desert settlements. For international interests it focuses within sustainable desert development, conventional techniques inspected through detailed investigations empowering designers and urbanists for integrating comparable modifications. Such approach support creation of climate-resilient communities, environmentally conscious of local ecosystem, lower footprint and culturally sustaining societies. The research represents an opportunity for using climatic responsive passive design strategies as design alternatives for contemporary household's developments in arid contexts. The findings from case studies proves that indigenous applied techniques are highly relevant to the context of sustainable development in desert settlements. On the other hand; the adopted passive integrated system reflecting an environmental sustainable design philosophy that prioritizes integration with environmental settings and respect the identity of the local community.

Keywords: vernacular desert settlements; passive design; environmental sustainability; climate-resilient communities; climate responsive design; Siwa.

1. Introduction

Arid desert regions are one of the greatest prevalent form of habitat in the world, occupying 14.2% of the planet's land mass. Almost a billion humans are resident in nations that are fully located inside this climatic pattern (Alharthi et al., 2025). The foundation of sustainable desert towns was built on the extraordinary significance of vernacular passive strategies for the desert environment, which encourage the sustainable use of local resources and efficient energy usage to boost resilience among communities (Alqalami, 2024; Gómez, 2023). The microclimatic requirements of desert towns were met, respectively, by using integrated systems in buildings and indigenous architectural construction techniques, which provide distinctive features of cultural and ecological sustainability. As a result, it plays a vital role in helping the local desert community to achieve their goals of sustainable development (Alqalami, 2024). In accordance with the need for climate control to fulfill optimum thermal environment of occupants, vernacular desert residences provide a superior solution in using less energy than modern ones. They employed an effective passive integrated system in urban and building pattern that might contribute to achieving zero developments (Tawil et al., 2018). In this context, climate-responsive design strategies can be effectively incorporated into modern buildings through the use of vernacular architecture vocabulary created by indigenous community to comply with local climate restrictions and sociocultural norms (Femmam & Sriti, 2022). Vernacular architecture is now seen as a sustainable architectural model. Aspects and features of this kind of design are the source of the tactics that currently form the foundation for environmental sustainability (Juan-Ferruses et al., 2024). The majority of scholars believe that conventional models in this context provide important insights into how to address criteria of environmental sustainability in modern practices (Haval, 2016). The creative application of ecological adaptability techniques in vernacular desert architecture is exemplified by multiple scenarios from various desert environments throughout the world. Middle Eastern and North African countries demonstrate the enduring value of traditional remedies and their capacity for adaptation to modern designs, particularly in challenging conditions. These narratives demonstrate the significance and global relevance of vernacular desert techniques for tackling today's environmental concerns in arid places and securing sustainability (Alqalami, 2024). Vernacular techniques in Middle Eastern desert settlement, which have long relied on conventional technology, have been shown to generate an environmentally responsible architecture that takes into account the demands of the native inhabitants and the

environmental arid context. These accomplishments were linked to settling on quantifiable environmental sustainability standards (Abdellatif, 1985). However, the architecture of hot arid deserts in North Africa have similar urban pattern characteristics like small streets and a compressed urban fabric. At the building design level, they are similar in that they use local construction practices and supplies with ability to absorb, store and release heat, brightly colored materials in the external enclosure, and limited apertures regarding a central courtyard as dominant passive eco-features (Mansour, 2014). In North African desert countries, vernacular design elements, building techniques, materials and sustainable use of resources within passive integrated system in planning and architectural design has a significant impact on the overall design process. It reaches sustainability state via adaptability to climatic conditions, environmental, and social demands. This is successfully achieved by mitigating extreme climate conditions while preserving cultural significance in desert architecture (Author after Alqalami, 2024). Environmental eco features, construction methods, materiality, and regenerative practices of local supplies integrated with each other's along a passive integrated systems through planning and design process. This strategy in vernacular community have a major influence in molding the entire composition of Northern African arid environment. It achieves the sustainable development goals of the native communities by flexibility in response to social, environmental, and climate challenges. This is accomplished by adaption measures with the severity of desert climate while sustaining the culture identity of the local society.

2. Problem identification:

Problem identification are discussed according to parameters affecting sustainable development of desert settlements in regarding to climatic responsive strategies of vernacular architecture. Sustainable development of desert settlements is a comparatively novel approach which turned out to be essential driven by the expansion arid region as a consequence of desertification. The practice of looking for new sites to establish new human settlements, as well as increasing the demand for crop supply, and the utilization of environmental assets were all factors in the development of desert environments (Golany, 1983). Globalization has caused inhabitants of arid regions to progressively abandon their traditional practices in favor of technology-driven building and the use of advanced supplies and urban amenities (Zhu, 2023). The individual's drive to progress with regard to modern urban adaptation comes at the expense of cultural integrity, social behaviours and ecological responsibility of the local community (Dahmani et al., 2024). In order to address the complications of poverty and degradation in environmental settings, underdeveloped countries are beginning to incorporate social and environmental considerations as key elements for desert-oriented development initiatives (Abou-Korin, 2002). In economically developing nations like Egypt, the norm prioritizes rapid growth over long-term prosperity. The majority of new settlements are constructed to support the expanding population without considering their long-term effects on the environment and sustainability of the local community (Ayyad & Gabr, 2013).

Conventional constructions in desert settlements have a series of dilemmas in maintaining the heritage status and legacy, which are connected to significant socioeconomic shifts, changes in the urban context, and advancements in technology (Benslimane et al., 2020). Other great challenges are facing desert communities for contemporary development including; incompatibility between the structure and its context, the extensive usage of non-renewable source of energy causing permanent ecological degradation, the utilization of supplies conflicting with extreme climatic conditions and unadaptable designs and impracticality of reuse (Esmaeili & Litkouhi, 2013). The Middle Eastern countries experienced a sharp rise in the use of mechanically operated air-cooled technology over the past few decades in order to ensure comfortable thermal conditions and withstand the extreme arid climate (Ali, 2018; Haval, 2016). There was a widespread shift from passive to active design principles in buildings, resulting with substantial power consumption and higher energy expenses for the occupants. In addition, it heightened carbon footprints causing a significant contributor to ecological imbalances and global climate changes (Haval, 2016; Ayala-Moreno, J. & Ayala-Moreno, A, 2024; Gómez, 2023). Contemporary desert settlements had lose the harmony between human activities and nature resulting in buildings designed without context, besides the lack of climatic responsive strategies in architecture design. Due to changes in ecosystem and culture of the community, certain practices of native techniques presently are not operating as intended. Learning basic principles of conventional construction and figuring out how to use them into standard development efforts to design new sustainable desert settlements is the main obstacle in this context (Kumari et al., 2020).

3. Aims, strength and novelty of the research:

This study focused on the role of low carbon desert communities in meeting the globe's carbon mitigation goals, maintaining sustainable energy supplies and lessening the effects of climate change globally through adopting vernacular passive strategies in desert applications of North African countries. An integrated sustainable standard for current and future urban planning and

architectural design in comparable arid environments are becoming more and more necessary. The study ultimately aims for bridging a wide gap of time by examining the alternatives of vernacular passive strategies to support resilient modernism in extreme arid contexts. This can be achieved by supporting the goals of sustainable development and indicators of responsible culture identity to fulfil the demands of sustainable desert communities. The study aims for deriving findings that acquirable from time-honoured traditional architecture practices initiated in the vernacular arid communities. It aims to highlight various passive strategies at urban and building design from chosen case studies and set a base line criteria that might serve as a framework of designing protocols for a model to arid desert settlements. In this regard, the research aims to evaluate the performance of the vernacular passive strategies in desert vernacular settlements regarding evidence based on environmental approach. The study contributes by manifesting main streams for an approach towards developing a zero carbon settlement in arid climatic regions inspired by vernacular desert practices. It contributes to contemporary sustainable architectural protocols by demonstrating legacy-based techniques that address climatic responsive strategies in arid areas. The study framework could be used as a benchmark for studies on energy efficiency of household's development in arid climates conducted by academics and corporate entities. The proposed checklist criteria were innovated to meet the special arid areas in general, being extracted from an analysed site in particular, and utilized for assessing acting levels of existing settlements regarding environmental sustainable standards. The research findings highlight its originality as it offers insights to vernacular architectural frameworks in desert settlements to be integrated into modern techniques. The novelty of this research reflects the role of planning strategy and passive design procedures that can be applied to improve outdoor and indoor thermal environment and managing climate responses of desert household's settlements at a preliminary stage of design process to achieve the concepts of sustainability during settlements life cycle.

4. Literature Review

The study explores literature reviews that are involved by engaging the fundamentals of environmental sustainability from vernacular desert settlements. It combines proof derived from earlier studies to advance perception on integrated passive design of climate responsive design strategies at scale of urban fabric and building design within environmental arid settings. Respectively, studies relevant for thermal environment of household's settlements within desert regions in North African countries will be determined. Many reviews highlighted the engagement of adaptable design in arid environment which contingent on bioclimatic conception. It outlines the basic principles, tactics, and advantages of using passive approaches at an architectural as well as urban extents. Moreover, they discover motivating practices in vernacular arid settlements which was blended to climate-adapted design features.

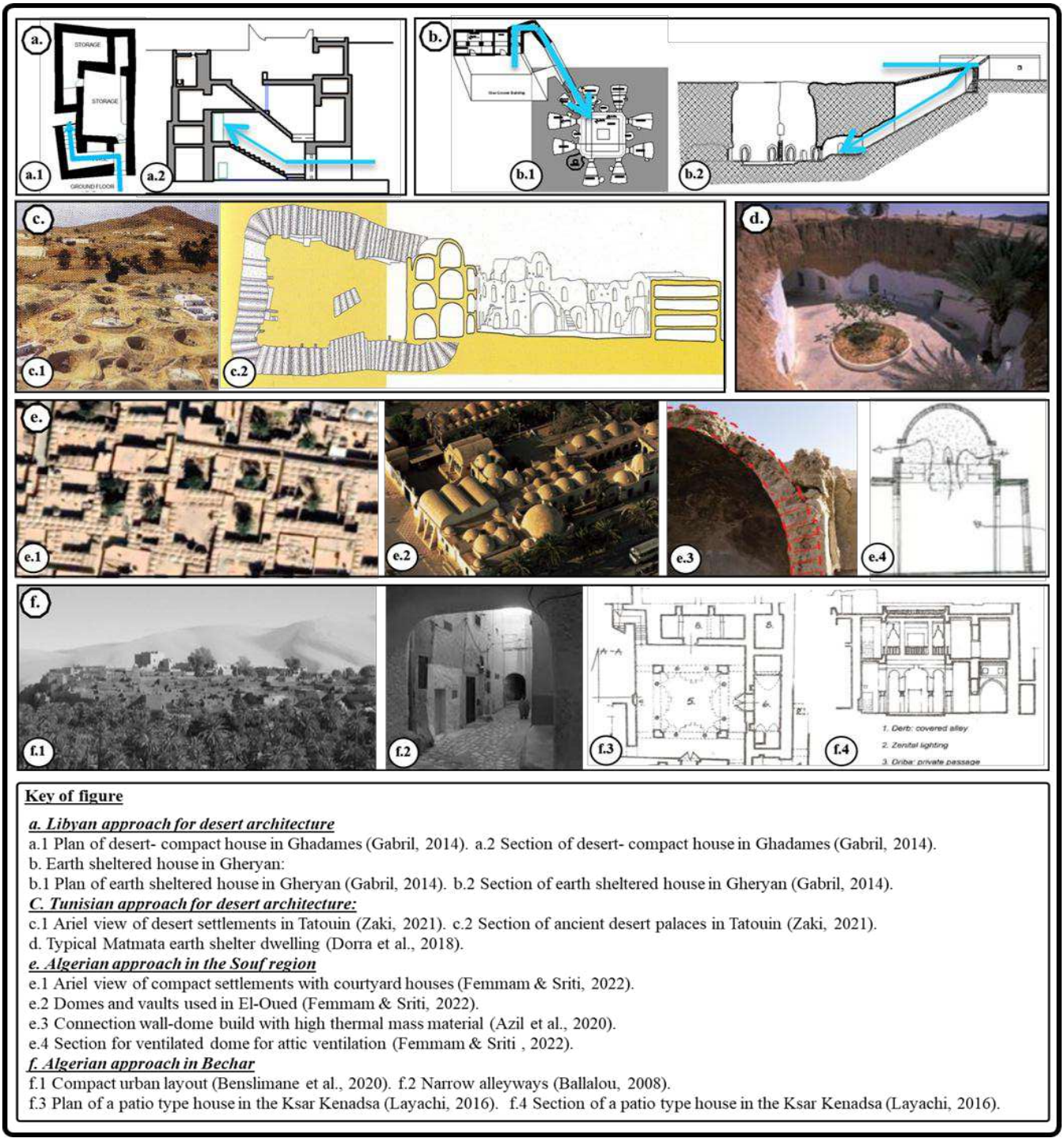
4.1 Experience of North African countries in desert architecture

A recent study in 2025 demonstrated a checklist for responsive climatic design criteria in vernacular habitation of Libya. It carried out a comparative analysis for various climatic regions with the goal of examining the key components of vernacular architecture in each of these respective regions. It concluded that indigenous architecture in Libya reflects innovative feedback to climate regime and ecosystem, within each terrain creating building styles that are appropriate for its unique characteristics and local settings. Thermally reflective materials have been employed in coastal structures; high thermal mass materials were used in arid regions to provide heat insulation, and regions with mountains made use of their topography to provide climatically sheltered environments. This study suggests adopting inspiration from vernacular desert architecture to be used in environmental sustainability of contemporary settlements that optimize ecological sustainability and preserve ecosystems (Huda, 2025). According to a study in 2017, the strategy of vernacular settlements in Libyan Sahara indicate a superlative strategy for fulfilling both adaptability and attributes of energy efficiency in arid environment. Therefore, the results of this study could assist designers in developing architectural concepts that optimize usage of energy while promoting occupant preferences, comfortable living, and sustainable community by employing passive design techniques learnt from traditional building practices. These results make it clear that socioeconomic and contextual variables coexist, improving the sustainability of the local community and its cultural versatility (Shahran et al., 2017). A research investigation conducted in 2013 presented a model of a Libyan community's desert home that provides climate-responsive architecture by constructing thermally appropriate man-made environmental settings. Additionally, it demonstrated the use of certain architectural techniques for resource-efficient buildings that take into account socio-cultural, and environmental constraints (Belhaj et al. 2013). Another study in 2018 examined the contribution of Libyan vernacular architecture in the development of sustainable communities in arid regions. The architecture of conventional homes for Ghadames settlement took into account a number of

passive features, including optimal alignment, the use of a central courtyard, massive thermal mass building materials, minimal openings, and earthy bright colors for the exterior. According to field assessments, troglodyte houses in Gharyan's arid zone offer an improved microclimate for the entire time round. On the contrary, Libyan home in the ancient Ghadames arid territory depends on regional construction supplies that serve to improve the household's climate adaptability. The study found that they employed an innovative design concepts and construction techniques that could potentially attain Zero-Carbon development, since they use roughly 66% a lower power than modern homes. It was also discovered that adopting passive solar strategies is the most efficient method to reduce energy demands for cooling and heating attributed to adaptability for local desert climate (Tawil et al., 2018). A recent study carried out in 2025 suggested a standard checklist for desert settlements at the Old City of Gharyan in Libya in order to achieve the goals of sustainable development of desert communities. This criterion originated from aspects of climatic versatility through passive ventilation and cooling, materiality, arrangement of urban spaces, and managing water resources. The effective system to manage water flow through distributing water into channels demonstrated inventiveness of the local community in utilizing local assets in a self-sustaining approach (Elbasha, 2025). An investigation carried out in 2008 in Ghadames town used an approach to adjust the building's indoor climatic conditions in response to the external environmental circumstances. Consequently, the design and material selection of the structures were incorporated into the external enclosure as a single cohesive system. According to a summertime field investigation, residents of vernacular structures consistently believe that their thermal comfort levels are higher than those of newer ones. The study came to the conclusion that, in terms of passive ventilation and thermal efficiency systems, the desert settlements of Ghadames were the most effective and adaptable for such climate variables because the local urban patterns and building designs offered helpful guidance for creating a sustained community (Almansuri et al., 2008). Another analysis for native settlements of Ghadames was carried out in 2002 to investigate the effectiveness of energy efficiency for passive systems in buildings through construction supplies, roofing and aperture designs. After careful examination, it was discovered that Ghadames conventional design responded to the severe arid environment by adapting, modifying and protecting. It came to the conclusion that Ghadames earthen development, which integrates perfectly with the surrounding landscape, is an outcome of indigenous technology in construction techniques, which falls in line with the community needs, cultural identity, environmental setting and proximity to the natural environment (Al-Zubaidi, 2002). An earlier study conducted in 2002 found that the design and structure features of Ghadames housing settlement contribute to the heat regulation for residences through the use of appropriate construction supplies and techniques of building systems. It recommended for considering native passive standards in applied integrated strategies in building design through the use of high thermal mass construction supplies, central courtyards and bright colors for heat reflection (Abrik & Al-Zubaidi, 2002). According to a study in 2016, Ghadames settlement and its conventional building scheme offers high energy performance techniques and an efficient carbon-neutral system. In an attempt to cool down the incoming air by evaporative cooling before it enters the urban area, multiple sidewalks are oriented to face the green park. Additionally, residential structures are thoughtfully positioned near the direction of the predominant wind. Moreover, the incorporation of daylighting and passive ventilation techniques in residential designs reduced the overall amount of energy needed (Albrassi & Farkash, 2016).

A study by Zaki in 2008 carried out a comparative analysis and assessment for the performance of some selected resort around the world in term of sustainability. It concluded that Tatouin in the south of Tunis with distinctive desert palaces and houses of old villages was a natural reflector towards respecting the environmental and social conditions which had succeed together in creating a sustainable community. Environmental sustainability was achieved with respect to applying groups of criteria including; using the local natural building materials, recycled materials besides; preserving the desert flora and fauna. Moreover, it takes full advantage of beautiful views of desert landscape and the mountain chains; preserved the ecologically important sites, geologic compounds, fossilized trees and marine excavations. The eco features of the scheme include using passive architectural method to create a thermal insulation from the arid climate and as a reflection towards the responsive climatic design. A checklist for evaluating acting level of Tatouin village was conducted based on environmental, social, culture and economic aspects of sustainability. Environmental parameters include minimizing environmental impacts, protection of natural resources, range of using natural materials & techniques; besides, architectural and planning performance to environmental settings (Zaki, 2008). A recent study in 2023 conducted a checklist for criteria applied in native Matmata housing and their impact on well-being. The criteria were based on group of factors including; the utilization of locally sourced supplies, the strategy of passive ventilation, daylighting concepts, passive solar protection, comfortable environmental conditions, sound insulating, nature-inspired design and cultural value. According to the study's findings, conventional

construction has significantly improved the quality of life for individuals throughout history by adapting to the distinctive requirements of the local communities. The applied passive strategies succeeded in creating a harmonious relationship between ancient settlers and their surroundings fostered a healthier lifestyles and conservation of local environment (Raslan & Saeed, 2023). The integrated passive system in some desert settlement in North African countries illustrated in (fig.1).



Key of figure

a. Libyan approach for desert architecture

a.1 Plan of desert- compact house in Ghadames (Gabril, 2014). a.2 Section of desert- compact house in Ghadames (Gabril, 2014).

b. Earth sheltered house in Gheryan:

b.1 Plan of earth sheltered house in Gheryan (Gabril, 2014). b.2 Section of earth sheltered house in Gheryan (Gabril, 2014).

C. Tunisian approach for desert architecture:

c.1 Ariel view of desert settlements in Tatouin (Zaki, 2021). c.2 Section of ancient desert palaces in Tatouin (Zaki, 2021).

d. Typical Matmata earth shelter dwelling (Dorra et al., 2018).

e. Algerian approach in the Souf region

e.1 Ariel view of compact settlements with courtyard houses (Femmam & Sriti, 2022).

e.2 Domes and vaults used in El-Oued (Femmam & Sriti, 2022).

e.3 Connection wall-dome build with high thermal mass material (Azil et al., 2020).

e.4 Section for ventilated dome for attic ventilation (Femmam & Sriti , 2022).

f. Algerian approach in Bechar

f.1 Compact urban layout (Benslimane et al., 2020). f.2 Narrow alleyways (Ballalou, 2008).

f.3 Plan of a patio type house in the Ksar Kenadsa (Layachi, 2016). f.4 Section of a patio type house in the Ksar Kenadsa (Layachi, 2016).

Fig. 1 The integrated passive system in some desert settlement in North African countries

4.2 Conclusion of literature review (research gap)

Although courtyard houses in vernacular desert settlements represent a key stone for passive design for thermal adaptation and sociocultural interaction, but the adoption of this approach alone is not adequate for high performance microclimatic conditions. This emphasized the need for integrating more than one eco features to create an effective integrated system to fulfill optimum control, modification and adaption to desert climate and thermal environment. Despite the fact that multiple academics have studied vernacular traditional houses in arid environment, they have not carried out a comparative investigation for desert household's settlements regarding integrated passive strategies based on criteria of environmental sustainability. The overall review on settlement development and low-carbon communities in arid environment revealed deficiency of empirical evidence in light of comprehensive environmental criteria for buildings within desert environment. Deep investigation of literature review concluded that perspective on climate responsive passive integrated system for arid climates appears to have irregular vision and limited insight. Moreover, most reviews neglect effect of passive integrated system at urban and building scope for desert settlements. Hence, this study will help to bridge the research gap on applying sustainable development of desert settlements at both scale of urban and building design. Accordingly, this research will highlight this integrated system to fulfill optimum objective of environmental sustainability.

5. Methodology

The methodology of the research is based on examining the urban fabric and building design of desert vernacular settlements in North Africa considering applied criteria. Accordingly, an evaluating model is used to evaluate the performing of these settlements considering the checklist for environmental sustainability in desert climates. The author had adopted a chain-linked approach that reflects the spatial framework of the research methodology, as presented in (fig. 2).

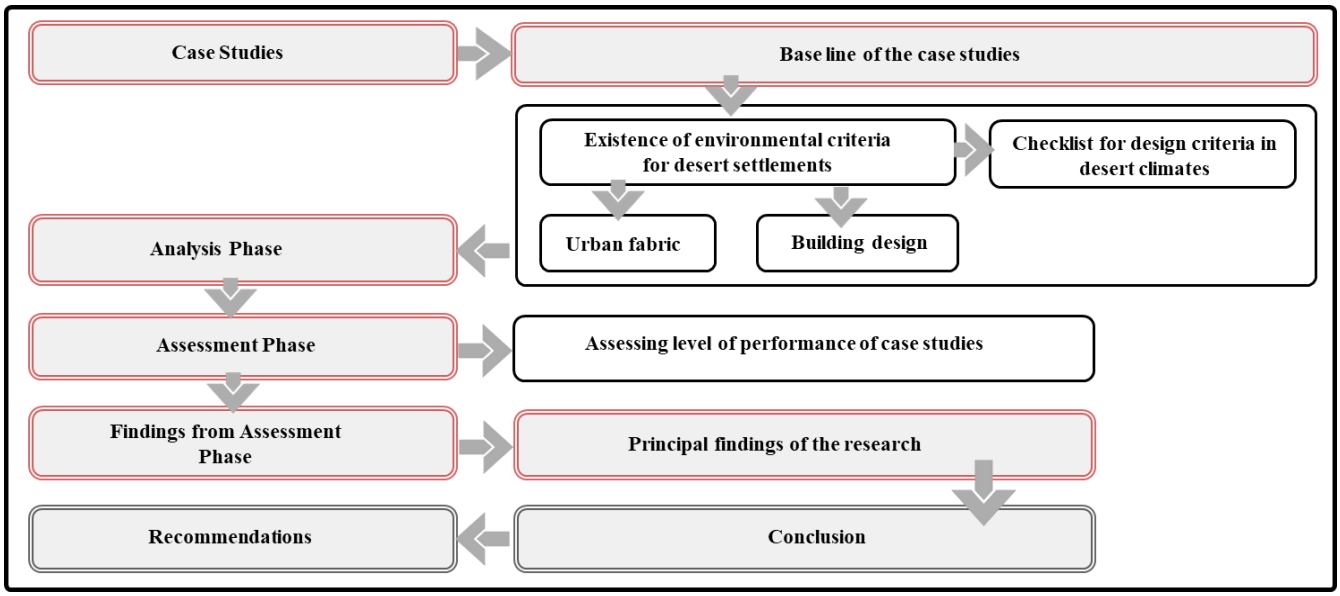


Fig. 2 the methodology of the research

6. Case Studies

Based on analytical approach, the environmental aspects of the selected traditional settlements will be investigated through a qualitative analysis to compare their thermal performance and climatic adaptability based on environmental criteria.

6.1 Base Line for Case Studies

The base line is framed by the formulation of a checklist for factors affecting environmental sustainability in desert environment. Respectively, these factors constitute the foundation for an effective passive ventilation system considering urban and architectural settings. Table 1 represents formulation of guide lines for design criteria in desert climates.

Table 1: Proposed checklist of criteria for integrated system applied to case studies under investigation

Attributes		Factors Affecting Criteria of Attribute	Value of Scoring
Layout context and urban fabric		Take advantage of natural slope and topography through spatial organization	1
		Full advantage of climatic conditions through cluster orientation	1
		Protection of urban fabric through compacted organization	1
		Protection of pathways from climatic conditions (intense sun heat)	1
		Protection from storms and dusty winds	1
Architectural design of buildings	**Passive ventilation**	Cross ventilation	1
		Attic ventilation	1
		Stack effect	1
	Passive cooling	Plantation and water elements	1
		Caves and underground structures	1
	Passive shading	Elevated rooftops (eaves) / sheltered canopies / arcades	1
		Shaded plantation	1
	Daylighting	Effective daylighting devices: skylight, openings, reflected mirrors , light shelves	1
	Glare protection	Adjusting openings location	1
	Heat insulation and control of heat	High thermal mass building materials	1
		Limiting the number and size of external openings	1
		Light colors of the exterior envelope	1
		Modifying the structure's orientation to lessen intense of solar radiation	1
	Structure system	Respect native construction technique	1
		Use native building materials	1
	The courtyard	Dominant eco features in all types of architectural setting.	1
CE (3R)		Adaptive reuse of old structures	1
		Recycling and upcycling of construction supplies	1
		Recycling of solid biological waste	1
		Recycling of grey water	1
Effective resource management		Exploiting natural resources in a sustainable manner	1
		Sustainable use of locally-sourced materials	1
		Maximize the use of sun and wind movement.	1
		Provided a sustainable source of energy from local natural resources	1
		Developed an effective system to manage water and rain harvesting	1
Energy savings		Minimizing energy consumption and reduction use of mechanical ventilation.	1
		Energy efficiency	1
		Reduce the total energy requirement	1
Conservation of local environment		Integrating with the local natural environment and landscape	1
		Harmonious relationship between humans and their surroundings	1
Total score of attributes in integrated passive system (optimum score)			**35 points**

Score ranking	**1-10**	**11-15**	**16-20**	**21-25**	**26-30**	**31-35**
Classification	**Very weak**	**Weak**	**Moderate**	**Good**	**Very Good**	**Excellent**

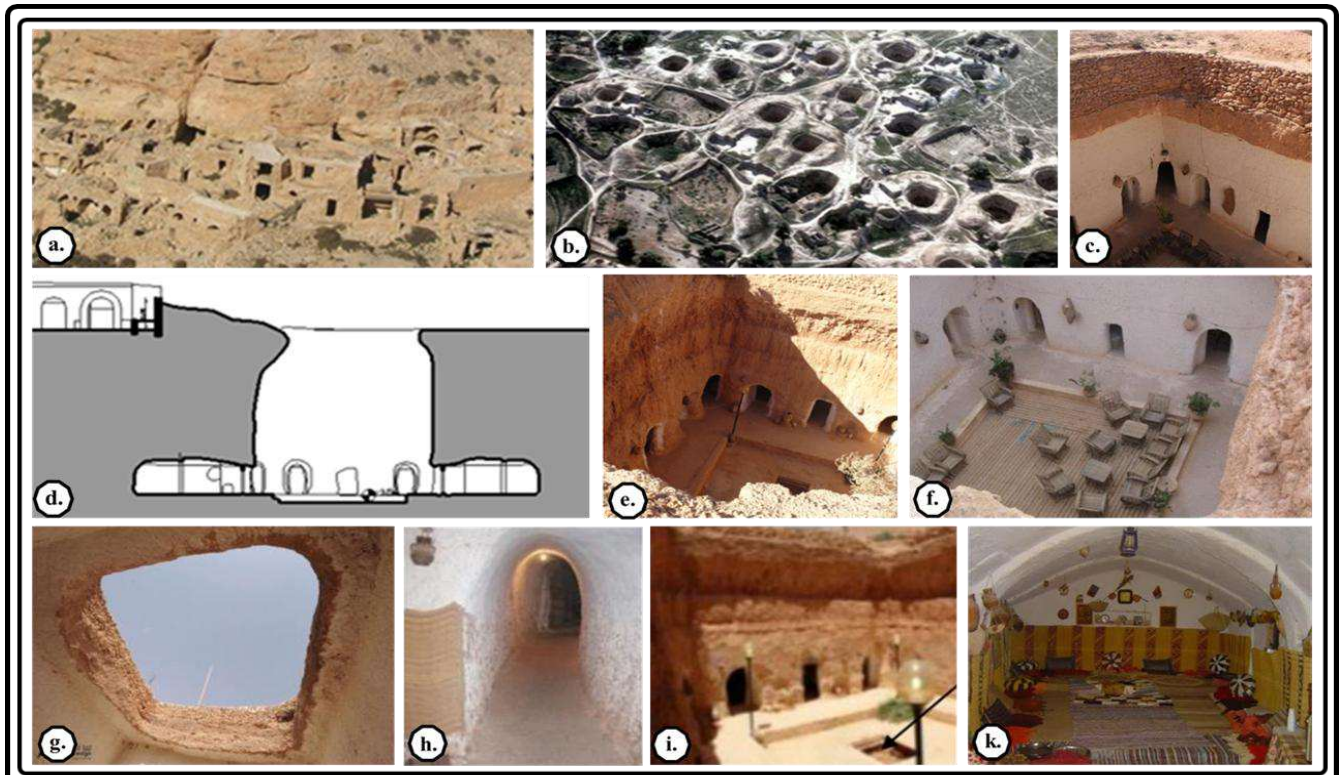
Source: Author after (Abd Elnaby et al, 2025), (Aboulnaga & Mostafa, 2019), (Albarssi & Farkash, 2016), (Almansuri et al., 2008), (Bassiouni et al., 2021), (Benyoucef & Suslova, 2019), (Rached et al., 2020), (Elbasha, 2025), (Raslan & Saeed, 2023), (Shahran et al., 2017), (Roussel, N., & Jaouën, M., 2018).
Notice: *this checklist act as a guided model for further desert settlements with similar environmental settings.*

6.2 Analysis of Case Studies

This sector is based upon an analytical approach to analyze performance of eco features in passive integrated system in desert household settlements, being integrated in urban pattern, building design and materiality.

6.2.1 Old City of Gharyan (Mountain House) in Libya

Gheryan offers ideal conditions for building earth-sheltered homes. It represents an optimal solution for ground-based passively warming and cooling by using the temperature of the soil. The depth of interior spaces has been restricted to control the flow of hot air inwards, while still maintaining the most effective orientation for the interior's zoning and opening accessibility. In order to offer shading for the courtyard for the majority of daytime, the wall length is proportional to the court's width at a 1:1 ratio. The area close to the living spaces was protected from the heat of the sun and rainfall by a protective shaded zone created by the arched courtyard enclosure (Gabril, 2014). Each of the drilled residences has a drainage ditch near its front doorstep to collect rainfall. The house is a local cooperative community dwelling because it is occupied by multiple families (Abo-elazm & Ali, 2017). This underground residence known as "troglodyte" exemplifies the best use of all available environmental resources. It is distinguished by the center courtyard, which serves as the house's fundamental feature (Shahran et al., 2017). Gheryan native architecture significantly corresponds to the climate and topography of the desert, reflecting its natural setting. The usage of mountaintop houses and cave structures as innovative design options that cleverly take advantage of the hilly landscape is what defines this particular form of architecture. The conceptual design of these caves distinguished by their enclosure in configuration, which symbolizes the adaptation development to the arid environment and the needs of the local community. It offers superior thermal insulation and a secure sanctuary from severe weather conditions. This kind of underground house was perfect for living in a desert since it maintained passive cooling in summertime and offered warmness in cold season (Elbasha, 2025). The integrated passive system in Old City of Gharyan is presented in (fig. 3).



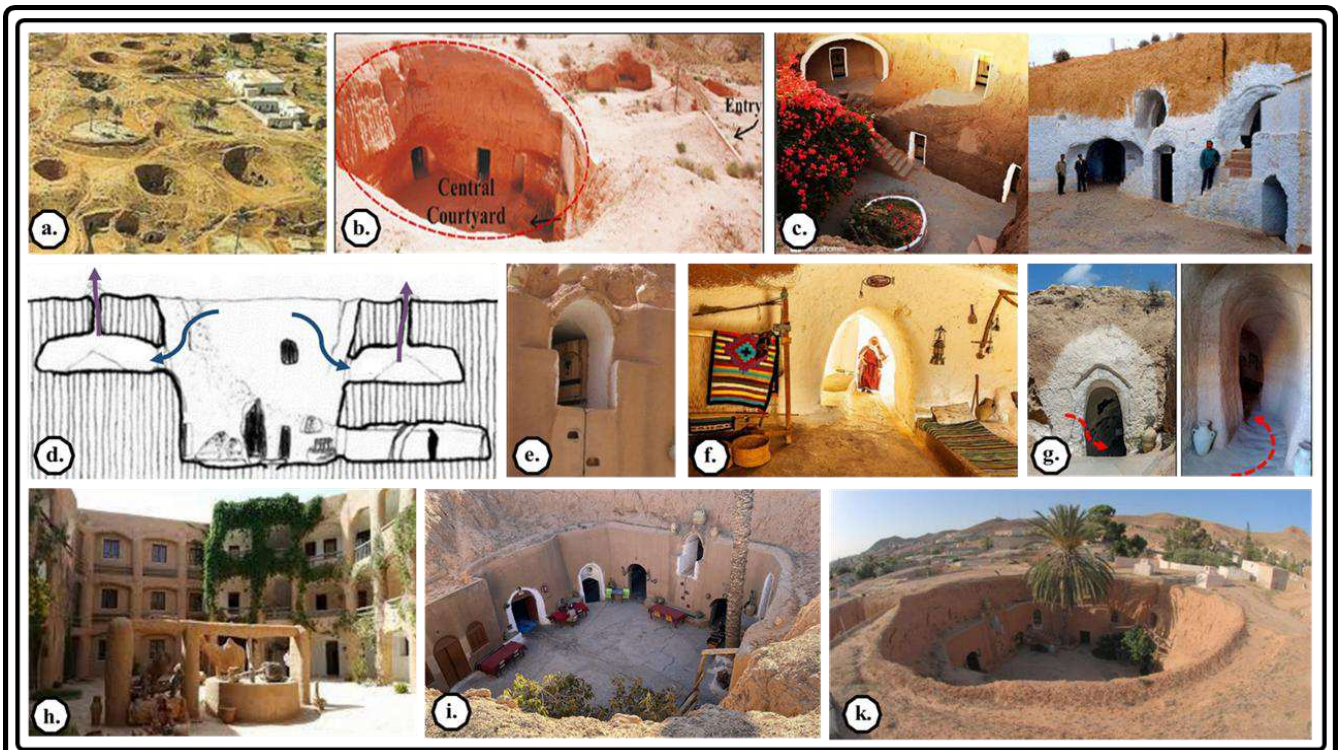
Key of figure

a. View of Troglodytes houses in Baqala city - Western mountain (Elbasha, 2025).
b. Troglodyte settlement in Gharyan (Elbasha, 2025). c. View of courtyard (Abo-elazm & Ali, 2017).
d. Section of Cave Houses in Old City of Gharyan (Gabril, 2014).
e. Openings design of cave house opened into inner courtyard for ventilation (Gabril, 2014).
f. Outdoor setting area in courtyard with limited planation (Mahmoud, 2016).
g. Upper outlet for ventilation and daylighting (Abo-elazm & Ali, 2017).
h. Interior view of inner shaded arch- shaped corridor (Bakoosh & Hajismail, 2024).
i. Water storage space in courtyard (Bakoosh & Hajismail, 2024).
k. Vault-shaped ceiling of living room with native environmental handcrafts (Elbasha, 2025).

Fig 3. The integrated passive system in the Old City of Gharyan (Mountain House) and Cave Houses

6.2.2 Matmata village in south Tunisia

The oriented vertical troglodytes dwellings created within the Dhahar Mountains are the defining feature of the Matmata territory (Kohli & Falhı, 2023; Benyoucef & Suslova, 2019). This housing pattern blends well with its native environmental context. The consistent combination of troglodyte structures within the natural setting is without a doubt one of their major advantages (Kohli, & Falhı, 2023). There are several passive climate adaptation strategies used in Matmata's desert regions for preserving coolness in the intense summer heat (Benyoucef & Suslova, 2019). Dwellings are entirely engulfed within the ground soil, including their roofing systems. As a result, inhabitants had improved interior environments due to the earth's hydrating capabilities. Dwellings rely only on natural air throughout the year, while the court serves as the primary source of ventilation for the interior spaces with an above aperture serves as a stack to exhaust the air by attic ventilation (Tafti et al., 2018). This effective passive ventilation system uses vents in the top chambers through overhead screens to keep out sandy particles and desert creatures (Raslan, & Saeed, 2023). In order to adapt to the natural setting, dwellings are excavated with courtyards similar to those seen in cave systems (Gaber, 2010). Only rooftop apertures with windows across the internal enclosure allow for daylight in the residential units arranged around the courtyard (Bozsaky, 2015). Each space has full connections to the centered courtyard, which provides a cooling breeze (Raslan, H. M., & Saeed, D. S., 2023). Matmata's tourist lodgings exhibit a distinctive assortment of traditional architecture features. These tourist lodgings reflect a successful practice of circular economy; based on adaptive reuse and rehabilitation of historic vernacular buildings as tourist destination (Kohli & Falhı, 2023). The integrated passive system in Matmata village is illustrated in (fig. 4).



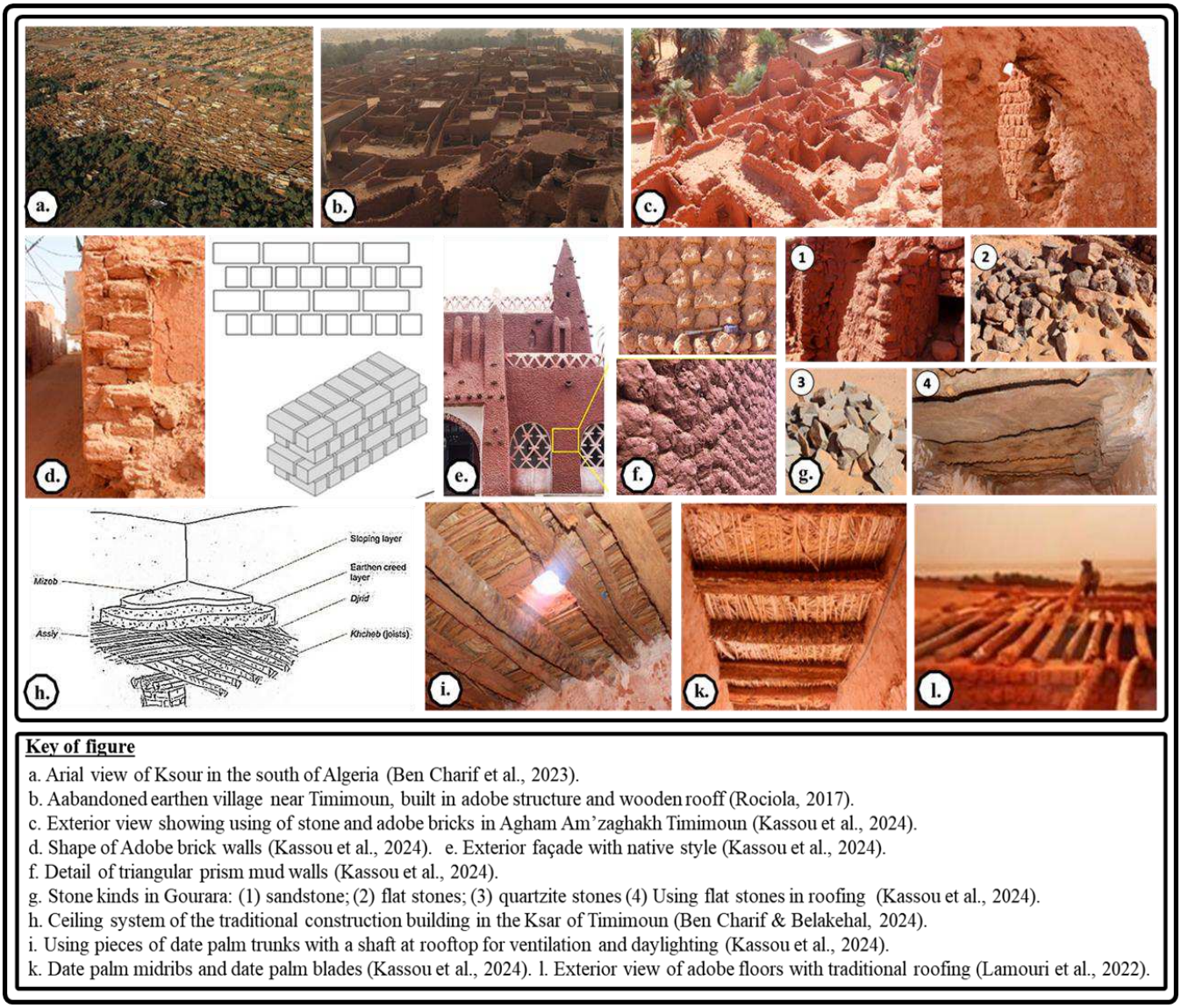
Key of figure

a. General view of vertical troglodytes of Matmata village (Driss & Kharrat, 2020).
b. Exterior view of household with inner courtyard (Raslan & Saeed, 2023).
c. Dwelling court with native plants for passive cooling and openings for ventilation and daylighting (Raslan & Saeed, 2023; Gaber, 2010).
d. Section for household showing air movement for passive ventilation (Benyoucef, & Suslova, 2019).
e. Accessibility to openings from courtyard. Small windows for heat protection (Raslan & Saeed, 2023).
f. Local motifs of Matmata dwellers: colorful woven mats, curtains and bed sheets, twined straw boxes and ceramic pots (Tafti et al., 2018).
g. In direct entrance to avoid storm and pollutants (Raslan & Saeed, 2023). h. Rehabilitation of Diar El Barbar Hotel (Kohli & Falhı , 2023).
i. Adaptive reuse of buildings: Marhala hotel (tripadvisor, n.d.).
k. Troglodyte house transformed into a Sidi Driss hotel (Kebaïli & Kebaïli, 2024).

Fig 4. The integrated passive system in Matmata village in south Tunisia

6.2.3 Ksar of Timimoun, Algeria

The planned communities of Ksar of Timimoun encircled by palm trees that define the urban fabric. Residences were built entirely of muddy soil, grouped in graded hills, and surrounded by courtyards with screened skylight. The adjacent walls provide shade for the extremely tiny sidewalks, which partially shielded against solar radiation in certain areas by fabrics and canopy structures. The sun can penetrated throughout the wintertime by considering the height of the building (Gaber, 2010). The dwelling has an open courtyard to allow passive ventilation and daylighting. By using light hues, the urban reflectivity would be further increased, resulting in less heat transmission within the building. Conversely, walls with a significant daytime heat retention rate guarantee a quick release of warmth at night (Ragette, 2003). Through the tiny holes in the top floor spaces, cross ventilation is produced. For the earliest inhabitants, the sole substance for construction readily accessible was earth. Accordingly, they employed sun-dried earth bricks as a building material (Gaber, 2010). Straw and stone are added to the combination to organically stabilize the primary raw earth. The structure system of the roof is made up of multiple segments, such as sandy lime plaster, palm fiber, palm leaves, palm trunks, and palm petioles. The spaces between oak timber are filled with an earthen-straw composite. The lower portion of the roofing structure is covered with lime mortar and constructed out of reeds (Lalali et al., 2025). The integrated passive system in Ksar of Timimoun is displayed in (fig. 5).



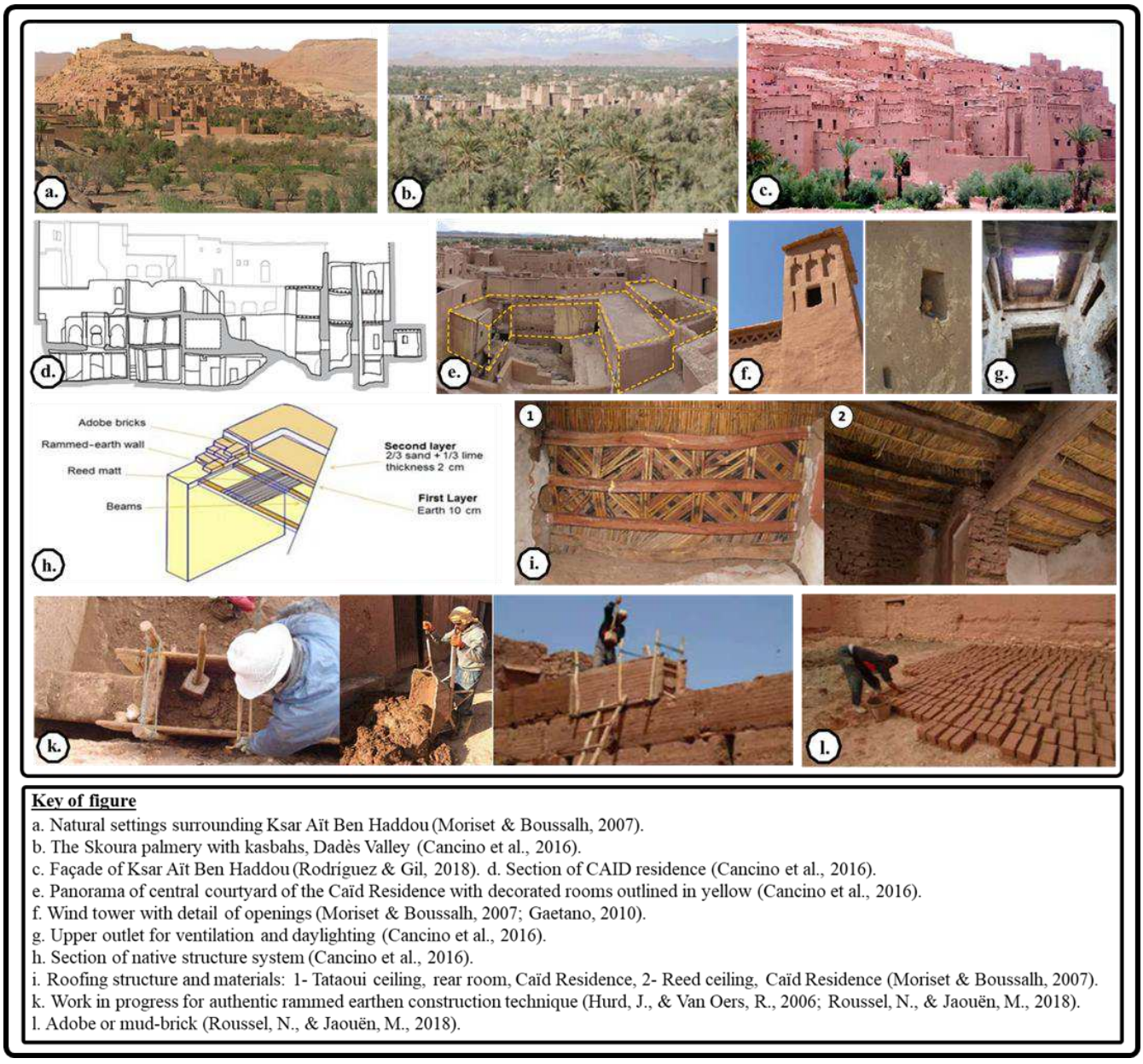
Key of figure

a. Arial view of Ksour in the south of Algeria (Ben Charif et al., 2023).
b. Aabandoned earthen village near Timimoun, built in adobe structure and wooden rooff (Rociola, 2017).
c. Exterior view showing using of stone and adobe bricks in Agham Am'zaghakh Timimoun (Kassou et al., 2024).
d. Shape of Adobe brick walls (Kassou et al., 2024). e. Exterior façade with native style (Kassou et al., 2024).
f. Detail of triangular prism mud walls (Kassou et al., 2024).
g. Stone kinds in Gourara: (1) sandstone; (2) flat stones; (3) quartzite stones (4) Using flat stones in roofing (Kassou et al., 2024).
h. Ceiling system of the traditional construction building in the Ksar of Timimoun (Ben Charif & Belakehal, 2024).
i. Using pieces of date palm trunks with a shaft at rooftop for ventilation and daylighting (Kassou et al., 2024).
k. Date palm midribs and date palm blades (Kassou et al., 2024). l. Exterior view of adobe floors with traditional roofing (Lamouri et al., 2022).

Fig 5. The integrated passive system in Ksar of Timimoun, Algeria

6.2.4 Ksar Aït Ben Haddou, Morocco

The traditional earthen design of this complex has notable historical significance, demonstrating its harmonious assimilation into the environmental settings. One of the elements that contributed to this kind of regional distinctiveness and architectonics was the adaptation to the environmental condition, which was linked to earthly building operations (Les Ateliers de Cergy-Pontoise, 2018). The distinctive composition of earthwork techniques in this complex including rammed earth and adobe works, demonstrating its very own accustomed architecture style (Cancino et al. 2016). Earth was selected as a building material because it is inexpensive and adaptable to the local climate and surrounding landscape (Les Ateliers de Cergy-Pontoise, 2018). Throughout the extremely sunny day, high thermal mass sun-dried brick was employed to reduce interior temperature fluctuations. The enclosed area of the courtyard has a practical purpose for establishing mild climate throughout the diverse urban environments of Morocco's typical Saharan homes. It guarantees natural daylight, passive ventilation and cooling; besides protection from sun heat and partial shade (Benyoucef & Suslova, 2019). The integrated passive system in Ksar Aït Ben Haddou, Morocco is displayed in (fig. 6).



Key of figure

a. Natural settings surrounding Ksar Aït Ben Haddou (Moriset & Boussalh, 2007).
b. The Skoura palmery with kasbahs, Dadès Valley (Cancino et al., 2016).
c. Façade of Ksar Aït Ben Haddou (Rodríguez & Gil, 2018). d. Section of CAID residence (Cancino et al., 2016).
e. Panorama of central courtyard of the Caïd Residence with decorated rooms outlined in yellow (Cancino et al., 2016).
f. Wind tower with detail of openings (Moriset & Boussalh, 2007; Gaetano, 2010).
g. Upper outlet for ventilation and daylighting (Cancino et al., 2016).
h. Section of native structure system (Cancino et al., 2016).
i. Roofing structure and materials: 1- Tataoui ceiling, rear room, Caïd Residence, 2- Reed ceiling, Caïd Residence (Moriset & Boussalh, 2007).
k. Work in progress for authentic rammed earthen construction technique (Hurd, J., & Van Oers, R., 2006; Roussel, N., & Jaouën, M., 2018).
l. Adobe or mud-brick (Roussel, N., & Jaouën, M., 2018).

Fig 6. The integrated passive system in Ksar Aït Ben Haddou, Morocco

6.2.5 Siwa Oasis, Egypt

The ability to adapt to climate variability is a defining feature of the native urban development in Siwa (Rached et al., 2020). Urban-scale environmental strategies; involve applying group of criteria for passive integrated system considering related thermal factors, building materials, eco features and other related environmental factors in Siwa Oasis. The urbanized feature of Siwa is defined by the concept of compact design, which is a way to lower the overall amount of built-up surface exposed to solar radiation. Confined, continuously covered, and enclosed roadways are necessary to offer a passive flow of breeze and protect against intense glare and hottest summer temperature (Bassiouni et al., 2021). An effective passive integrated system to provide adaptable microclimatic preferences is reflected in the compacted design where nearby buildings are shielded from solar radiation and graduated restricted pedestrian sidewalks is protected against arid environment (Mohamed et al., 2020). The integrated passive system applied in desert settlement of Siwa is displayed in (fig.7).

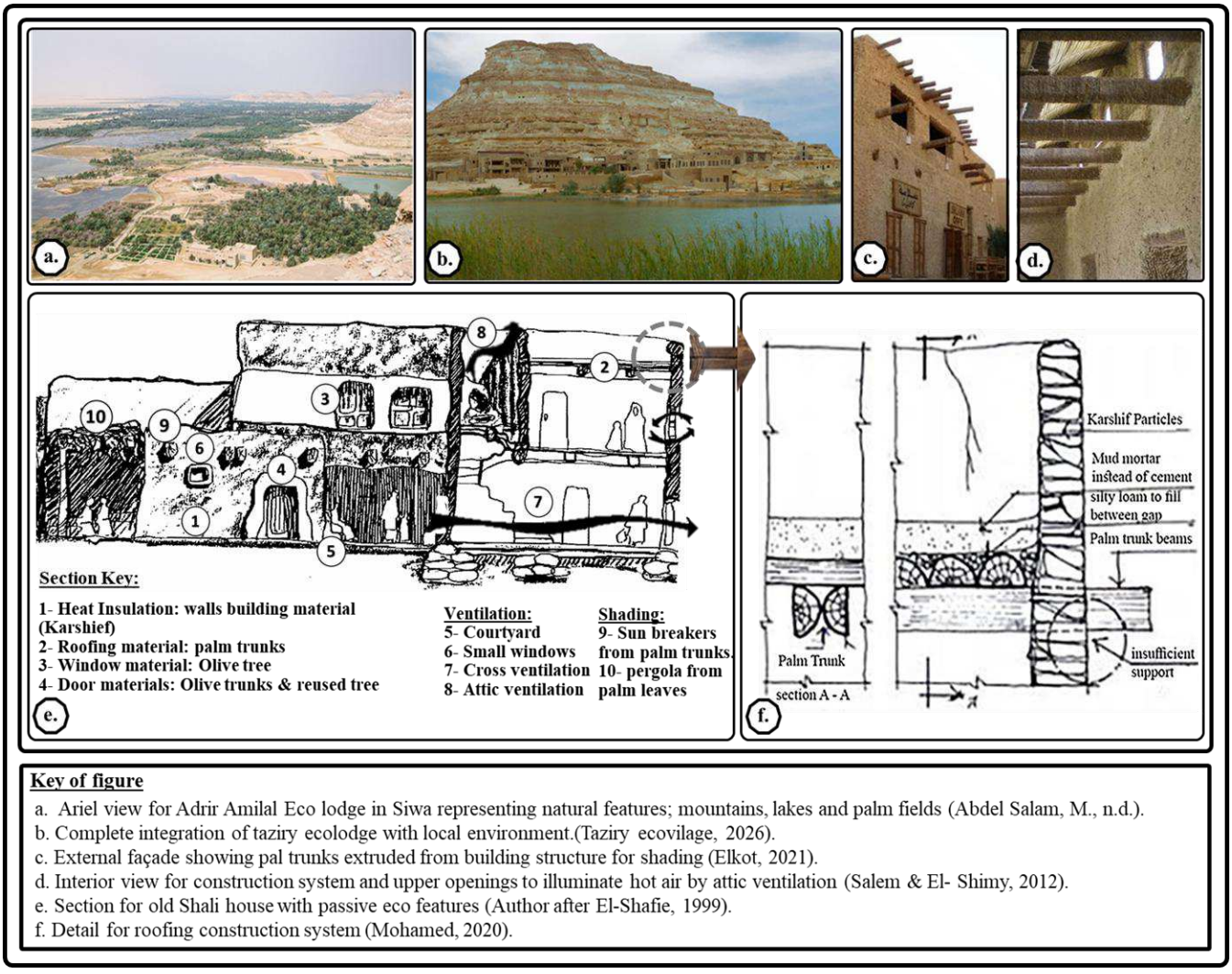


Fig 7. Passive integrated system applied in desert settlement of Siwa

6.3 Assessment of Case Studies

The climate-responsive design techniques employed within case studies function at multiple levels including: urban fabric and architectural design; as presented in table 2. The response of the building to climatic conditions were expressed through passive ventilation, cooling, shading, daylighting and glare control, heat insulation and control of heat, structure and integration of courtyard in design process. Other attributed factors were incorporated such as; circular economy, conservation of the local environment, effective resource management and energy savings.

Table 2: Assessing level of performance of case studies considering passive integrated system in design process

Case Studies	Attributes of Criteria and Affecting factors																						
	Layout context & urban fabric					Architectural design of buildings																	
						Passive ventilation			Passive cooling		Passive shading		Lighting	Glare control	Heat insulation and control of heat				Structure		Court yard
	Take advantage of natural slope and topography	Full advantage of climatic conditions	Protection of urban fabric	Protection of pathways from climatic conditions	Protection from storms and dusty winds	Cross ventilation	Attic ventilation	Stack effect	Plantation and water elements	Caves and underground structures	Elevated rooftops (eaves)/ sheltered canopies	Shaded plantation	Effective daylighting devices: skylight, openings	Adjusting openings location and eaves	High thermal mass building materials	Limiting the number and size of external openings	Light colors of the exterior envelope	Modifying the structure's orientation	Respect native construction technique	Use native building materials	Dominant eco features in all types of buildings
Old City of Gharyan	✓	✓	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓
Old Matmata	✓	✓	✓	✗	✓	✗	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓
Ksar of Timimo-un	✗	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Ksar Aït Ben Haddou	✓	✓	✓	✗	✗	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Siwa oasis	✗	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Case Studies	Attributes of Criteria and Affecting factors													
	Circular Economy (CE)				Conservation of local environment		Effective resource management					Energy savings		
	Adaptive reuse of old structures	Recycling and upcycling of construction supplies	Recycling of solid biological waste	Recycling of grey water	Integrating with the local natural environment and landscape	Harmonious relationship between humans and their surroundings	Exploiting natural resources in a sustainable manner	Sustainable use of locally-sourced materials	Maximize the use of sun and wind movement.	Provided a sustainable source of energy from local natural resources	Developed an effective system to manage water: rain harvesting	Minimizing energy consumption & reduction use of mechanical	Energy efficiency	Reduce the total energy requirement
Old City of Gharyan	✓	✗	✗	✗	✓	✓	✓	✓	✗	✗	✓	✓	✗	✓
Old Matmata	✓	✗	✗	✗	✓	✓	✓	✓	✓	✗	✗	✓	✗	✓
Ksar of Timimo un	✓	✗	✗	✗	✓	✓	✓	✓	✓	✗	✗	✓	✗	✓
Ksar Aït Ben Haddou	✓	✗	✗	✗	✓	✓	✓	✓	✓	✓	✗	✓	✗	✓
Siwa oasis	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

This assessment is based on criteria for passive integrated system illustrated in table 1; besides; analysis of applied passive system for each case study.

7. Findings from Assessment Phase

Siwa oasis had reached the highest score ranking among other desert destinations under investigation. The reasons of such result, because it respectively fulfilled the attributed criteria related to layout context, urban fabric, attributed architectural design of buildings including; passive ventilation, cooling, shading, daylighting, control of heat and glare, preserve of native pattern in building materials and construction techniques. Moreover; they possess innovative methodology for circular economy practices including adaptive reuse of abonnement structures and upcycling of natural supplies and wastes. The construction of buildings in Siwa Oasis relies on the use of local environmental materials, which plays a major role in preserving the cultural identity of the oasis. In addition, this approach contributes to enhancing environmental and economic sustainability since it reduces waste and minimizing the costs of transporting materials from outside the region by resource availability. Siwa Oasis is a prime example of sustainable building principles based on local environmental resources. The use of local materials and native construction techniques reflecting a natural integration with the surrounding environment. The oasis's environmental design plays a pivotal role in reducing the negative impacts of traditional construction by reducing the carbon footprint and providing natural thermal insulation that suits the nature of the desert climate. Moreover, it reflects Siwa rich cultural heritage and helps preserve its unique identity. Relying on locally available natural materials not only reduces costs, but also ensures effective confrontation with the harsh climatic conditions of the region. This approach not only contributes to sustainable construction, but also positively reflects on promoting eco-tourism in the oasis, as visitors have the opportunity to discover an exceptional architectural style that is a global source of inspiration in the field of sustainability. Every local resources employed to build Eco Lodges are recyclable, and consequently there is no wastage during life cycle of the buildings. Siwa is considered to be a model for sustainable development that ensure linkage between past and present, local community and visitors related to ecotourism, through optimum managing of available resources and creation of special micro climatic condition.

The proposed checklist presented in (table 1) for the assessment criteria had succeeded in evaluating the acting performance of applied passive integrated system in Siwa. The results of evaluating the performance of case studies considering applied passive integrated system is shown in (table 3).

Table 3: Findings from the assessment of case studies' performance with regard to applied passive integrated systems.

Case studies	Score Ranking for Applied Attributes of Criteria and Affecting factors considering Passive Integrated system	Classification
Old City of Gharyan	21 points	Good
Old Matmata	25 points	Very Good
Ksar of Timimoun	27 Points	Very Good
Ksar Aït Ben Haddou	26 Points	Very Good
Siwa oasis	33 Points	Excellent

8. Principal findings of the research

The proposed checklist criteria by the author had witnesses great successful in assessing acting of passive integrated system for chosen case studies. Earthy architecture of desert environments proofs complete integration with the natural environment as a result of the native technology used in urban fabric, building envelope, structure system and sustainable use of the local materials, which corresponds to the community, ecological context and closeness to geography.

This study adopted a combined methodology involving comparative case studies analysis, checklist matrix criteria and evaluating models for assessment measurement. This unique approach of the research could serve as a model for other scholars

for detailed inspection encompassing passive responsive climatic strategy correspondingly or within alternative bioclimatic areas. Similarly, passive integrated system including natural ventilation strategies, passive cooling, heat insulation and shading can be applied in different climates to create a microclimatic resilience communities. The study's findings possibly put into practice as a model for the appraisal of current and proposed settlements development through evaluating the implications of environmental drivers, materiality, building methods and behavioral adaptation and energy consumption rate within desert household. Moreover, the study proved that native desert architecture considered a reference and valuable inspiration for contemporary sustainable development within arid that responds to the desert settings through: protection, modification and adaptation.

9. Conclusion and Recommendations

The study proves that vernacular adaptive practices in North African countries have been successful in establishing permanent human settlements in extreme arid environments. It achieved environmental sustainability with ecological settings through energy efficient passive design strategies and effective integrated system in household's development through urban pattern and building design. The adoption of this sustainable approach in similar environmental context is possible to create contemporary desert settlements. The previously analyzed insights of vernacular built settlements in North African desert environment provide valuable lessons for contemporary urban planners and architects to inspire while seeking to create sustainable, climate-responsive urban environments in desert regions. It is inevitable to push the boundaries by deeply understanding the principles of vernacular techniques and the criteria of environmental sustainability that properly have a practical inspiration to create efficient contemporary responsive climatic design.
The study spotlights the need for actions on energy efficient design principles of vernacular settlements in arid regions which regarded as adaptive comfort model. By adopting passive integrated systems, we can support the conservation of resources and energy and improve optimal comfort and environmental quality along with further advantages.

The research suggested further recommendations to support creation of climate-resilient communities in desert environment these recommendations include;

- Use the proposed model at global context for evaluating further case studies that possesses similar environmental settings.
- Carrying out advanced investigation to determine the genuine consequence of the vernacular passive strategies in desert environments. Computer modeling for passive integrated system enables the assessment of climatic zones, optimal atmospheric conditions and consumed power capacity across diverse dimensions.
- It is advisable to integrate passive design strategies adopted from successful vernacular practices with active design strategies derived from sustainable energy in a hybrid system to fulfill SDG of desert communities. Respectively, hybrid integrated systems should be combined within contemporary development practices of desert regions to maintain environmental balance between passive and active systems and maximizing sustainable use of local natural resources.
- Designers shall take into account climatically adaptive approach and energy efficient design strategies in the early design stages for extreme conditions like arid desert climates and should rely on using passive integrated systems adopted from successful vernacular practices.
- The recommended passive integrated system applied for current and future practices in desert environment should reflects a successful employment of four natural renewable resources in environmental treatments at urban fabric and building envelope in favor of energy and materials used.
- By incorporating certain design adjustments and sustainable procedures, historic buildings in desert tourist destinations can be transformed into eco-lodges that maintain the community's indigenous character and cultural identity while maintaining its distinctive historical value.
- Needs for further studies to highlight the capability of vernacular desert settlements in circular economy practices through adaptive reuse of ancient historic buildings that support sustained tourism development.

Declarations:

Conflict of Interests

The author claims of absence of any competing interests.

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Sole contribution of the author in conceptualization, funding acquisition, methodology, formal analysis, investigation, writing, reviewing and editing.

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Data availability statement:
The data supporting the findings of this study are derived from published literature, publicly available reports, and documented architectural case studies, all of which are cited in the manuscript. The analytical framework, assessment criteria, the case-studies assessment matrices and comparative findings developed during this study are presented in the article and its supplementary materials, where applicable.

Clinical trial number: Not applicable. This study does not involve a clinical trial.

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Corresponding author: Dr. Ahmed Ibrahim Samir
Email: ahmed-samir@eru.edu.eg

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