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A Sustainable Digital Framework: Analysis of Sustainable Environmental Design Indicators for the Sultan Complex in the City of Najaf

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ABSTRACT

Contemporary architecture is undergoing a fundamental shift towards integrating sustainability and digital technology as a strategic approach to reducing environmental impact and achieving operational efficiency in urban environments. However, the absence of a national system or a comprehensive scientific framework for quantitatively measuring sustainable environmental design indicators (SIDs) limits the effective integration of environmental and digital performance at the early design stages. This research aims to develop a scientific and standardized framework for measuring SIDs and analyzing their practical performance through a real-world residential case study: the Sultan Residential Complex in the city of Najaf, Iraq. The methodology adopts a quantitative performance-based approach, in which key indicators were extracted from international literature and assessment systems, measured using standard equations and simulation–based analysis, and compared with global benchmarks. The extracted indicators fall under four main criteria: thermal comfort, energy strategies, environmental compatibility, and site management. The results reveal strong performance in thermal and energy-related indicators, satisfactory indoor environmental quality (IEQ), and relatively weak performance in site-related and ecological indicators. The study concludes that the proposed framework provides a replicable and scientifically grounded tool for evaluating sustainable environmental design and can support the development of a national system for digital integration in sustainable architecture within Iraqi and Arab cities.

1. INTRODUCTION

The architecture and urban planning sector has witnessed a rapid knowledge transformation in the last two decades. This transformation includes integrating environmental sustainability principles into design, construction, and operational processes. This is in response to global climate challenges such as global warming, depletion of natural resources, and the decline in the quality of the urban environment. In this context, the concept of sustainable environmental design has emerged as an integrated approach that seeks to reconcile human needs with energy efficiency, environmental justice, and economic viability throughout the building's lifecycle [1].

Despite this scientific progress, recent systematic reviews indicate a clear lack of integrated frameworks for measuring environmental indicators within local settings in the Middle East, particularly in cities with hot, arid climates such as Najaf. The climatic characteristics of these areas differ from the European models upon which most international standards are based.

Addressing this research gap, this study aims to extract, classify, and measure sustainable environmental design indicators (SIDs) in the Sultan Residential Complex in Najaf. This is achieved through a methodology that combines quantitative and descriptive analysis, based on international standards, and builds a standardized database that can be adopted to evaluate sustainable environmental performance in Iraqi residential projects. This paves the way for future digital integration into analysis and simulation in Najaf, providing a scientific framework to help designers and urban policymakers improve environmental performance and thermal comfort in hot, arid climates.

Recent literature shows that measuring SIDs has become a key focus in the development of performance-based architecture. It serves as an essential analytical tool for evaluating the energy and environmental performance of buildings throughout their lifecycle, enabling measurement of a project's compliance with international sustainability standards through comparable, analyzable data [2]. These researchers developed a multidimensional framework for classifying indicators into three main categories: environmental, social, and economic, emphasizing the importance of linking quantitative indicators with site-specific climatic analysis in the early design phases.

In the same vein, Abdel-Basset et al. [3] developed an analytical model for evaluating sustainable design in developing countries using the Multi-Criteria Decision-Making (MCDM) approach. The analysis demonstrated that assigning weight and importance to each sustainability indicator helps formulate design priorities and achieve a balance between energy efficiency and economic feasibility. As for Aram [4], he focused on integrating environmental indicators into urban analysis in hot environments, showing that adopting precise quantitative indicators, such as operating temperature and energy efficiency, can improve performance by 25% to 40%.

In a recent study, Mandičák et al. [5] indicated that digital technologies such as Digital Twins and BIM have become essential for analyzing environmental indicators. They enable integrating climate data and digital simulations to evaluate performance before actual implementation. This approach aligns with what Stamatopoulos et al. [6] proposed, emphasizing that enhancing the climate resilience of buildings begins by building a comprehensive database of quantitative indicators, including natural ventilation, lighting, energy efficiency, and water management.

The study presents a simulation-based proposed approach to assessing natural ventilation potential and passive design using an advanced automated analytical methodology that provides accurate results to support early design decisions [7]. Furthermore, Kurniawan et al. [8] demonstrated that energy efficiency indicators, such as total wall and roof heat transfer (OTTV) and RTTV, are standard tools for assessing building efficiency in hot climates, and that integrating energy analysis with environmental modelling enhances measurement reliability.

Ourghi et al. [9] and Karimi et al. [10] provided empirical evidence of the relationship between building form and energy consumption in hot and humid climates. The study indicated that improving building proportions and solar orientation can reduce energy load by more than 30%. These findings align with the general trend toward developing quantitative measurement systems based on accurate environmental simulations to integrate thermal performance, environmental comfort, and the physical sustainability of buildings.

Analysis of the literature reveals that measuring SIDs is among the most mature scientific trends in architectural sustainability research. It has shifted from a descriptive approach to a quantitative evaluation grounded in data and digital simulations. Studies have highlighted the importance of adopting comprehensive quantitative indicators that encompass environmental, social, and economic aspects to assess building performance accurately [2-4]. Other researchers focused on integrating digital analysis tools such as BIM and Digital Twin into the environmental assessment process to enhance measurement accuracy and predict energy performance [5, 8].

1.1 Environmental architecture

In today's literature, environmental architecture refers to a design methodology of the academic that achieves a balance between environment, social and economic during planning period-operations-salvage or demolition. It tries to ensure resource efficiency and obtain a lower carbon footprint, while improving living standards [4]. This is founded on basic tenets, among others climate-fit of the shape and positioning of architectural volumes, use of low impact materials, maximized use of natural light and air movement, employment of water harvesting and recycling systems, as well as advanced digital tools for design decision making [4, 5].

Recent research has shown that early-stage environmental performance prediction tools, by simulating on an elemental basis, improve the accuracy in environmental performance predictions and decrease the dependence on energy-intensive mechanical strategies to achieve such [11, 12].

At the city scale, recently, Algburi et al. [13] have emphasized the necessity for digitally measurable and quantifiable indicators (e.g., temperature, wind speed and air quality) to continuously determine the sustainability of districts and buildings especially in hot and arid areas necessitate advanced design adaptions. As such 'environmental architecture' nowadays constitutes a path of 'development' that fuses local climatic knowledge with digital analysis to conceive an effective scientific device for shaping more efficient and resilient buildings and cities in response to climate change [14].

1.2 Sustainable environmental design

Environmental design is an architectural and urban approach that integrates climatic considerations and natural resources into the design, planning, and construction processes. The goal is to achieve a balance between functional performance and minimizing environmental impact throughout the building's lifecycle [4].

This approach is based on fundamental principles, including maximizing natural ventilation, utilizing daylight, integrating green spaces into the built environment, and using local, low-emission materials. This is based on a thorough analysis of the site's climatic characteristics [15]. Recent research indicates that environmental design has moved beyond traditional solutions such as shading and thermal insulation, relying increasingly on digital simulation and airflow modelling. Using tools such as ENVI-met and CFD enables evaluation of thermal performance and climatic comfort before implementation [15, 16]. Other studies confirm that applying this approach enhances the climate adaptability of cities and buildings by integrating vegetation, improving urban orientation, and reducing thermal stress, especially in hot and arid environments [17].

Accordingly, it could be argued that environmental design is a bridge from sustainable architecture to digital transition. It integrates classical climate control with innovative digital analytics to drive optimal economic and environmental performance.

Sustainable architecture is based on an inclusive green design approach, in which social, economic and environmental parameters are blended into the architectural planning and designing of a building. This promotes optimal use of resources, reduces waste and emissions and generally improves the lives of residents [18]. This concept is based on a set of principles, including minimizing energy and water use, maximizing thermal performance, using low-impact materials promoting social justice in the development of built environments [18].

In recent literature, sustainable design is deemed a vital means to help reach the SDGs, in particular, climate and energy-related ones (United Nations, 2019). According to research, using this methodology in urban construction can decrease the carbon emissions from buildings globally by 40%.

Sustainable design has similarly been transformed by the digital revolution. Tools like environmental simulation, digital twins and BIM allow for better assessment of design options, thus making data-driven decisions from early stages of a project more possible [19]. Studies have indicated that combined with the environment requirements, these tools will contribute to long-term thermal performance and energy use efficiency [20, 21].

Hence, sustainable design is not a passing environmental fad but an inclusive approach that merges technological advances with social and economic sensibility; it is also the linchpin in the making of a more durable sustainable future for city life.

Sustainable Environmental Design is an integrative approach through which traditional environmental design, including aspects such as climate compatibility, energy efficiency and resource management, can be introduced into the three dimensions of sustainability - environmental, social, and economic. It seeks to deliver a built environment that minimises carbon footprints, maximises human well-being and sustains economic viability over the life of the project [22].

This is a return to a more natural sustainable way of thinking, where it's not just the technical solutions like insulation or shading. But it also contains embedded socioeconomic analysis on the design and operational level [23].

From a social perspective, researcher's emphasis that sustainable environmental design has become a tool for promoting urban justice and equitable access to public spaces, as well as improving the quality of life. This is particularly true in hot, dry residential environments, where thermal comfort and natural ventilation are pivotal to enhancing health and community well-being. Simulation studies in hot climates have shown that designing urban blocks and street patterns using environmental analysis tools, such as ENVI-met, can reduce thermal stress by 20–35% in densely populated residential areas [11].

From an economic perspective, sustainable environmental design is a cornerstone for achieving long-term financial efficiency through lifecycle cost analysis (LCC) and the integration of circular economy principles into construction and operation processes. Research has shown that adopting tools such as BIM and Digital Twin in materials and energy analysis can improve resource allocation, reduce waste, and extend building lifespan [24, 25].

Recent research in hot Arab environments highlights that socioeconomic challenges, such as the high initial cost of sustainable projects and weak local environmental awareness, are among the most prominent obstacles to adopting sustainable design, which calls for launching financial incentives and environmental awareness programs to ensure the sustainability of these practices and their societal acceptance [26].

Therefore, sustainable environmental design today represents an integrated strategic framework that combines technology, environmental analysis, social justice, and economic stability. This makes it a fundamental pillar for developing hot and arid cities like Najaf towards more resilient, equitable, and sustainable urban environments.

1.3 Benefit of sustainable environmental design

Recent studies have shown that adopting sustainable environmental design achieves a comprehensive set of environmental, economic, and social benefits that extend beyond energy performance to include improved quality of life and climate resilience in cities.

From an environmental perspective, this approach contributes to reducing energy and water consumption, decreasing carbon emissions, and improving resource efficiency. This leads to a 20–40% reduction in the environmental footprint of buildings compared to traditional design [4]. Field analyses have also shown that applying passive climatic design principles, such as natural shading and cross-ventilation, improves thermal comfort, thereby reducing the need for mechanical cooling [11].

From a social perspective, sustainable environmental design is an effective tool for promoting public health, spatial equity, and social well-being. It is closely linked to indoor air quality, natural lighting, and user comfort. Studies have shown that green buildings reduce absenteeism and improve individuals' cognitive and psychological performance [27]. Recent reviews have also confirmed that social sustainability is a cornerstone of modern urban planning, as it promotes community participation and equitable access to services [28].

From an economic perspective, sustainable environmental design offers tangible long-term financial savings by reducing energy and water consumption, lowering maintenance costs, and extending building lifespan [29]. Global studies indicate that investment in sustainable buildings yields an economic return exceeding the initial cost through improved operational efficiency and reduced waste [30]. Furthermore, behavioral research has shown that individuals are increasingly willing to pay higher prices for housing or to work in environmentally friendly buildings due to the comfort, health, and quality of life they provide [31].

From an adaptive perspective, sustainable environmental design is a strategic tool for climate resilience. It enhances buildings' and communities' ability to cope with climate change and rising temperatures in hot, arid environments by integrating natural solutions with smart technologies [31].

Therefore, it can be said that the benefits of sustainable environmental design extend across environmental, social, and economic dimensions. This makes it a strategic option for enhancing the sustainability of cities and communities, especially in regions with hot climates, such as Najaf.

1.4 Sustainable architecture

Sustainable architecture is defined in contemporary literature as a comprehensive design approach that seeks to balance human needs, the environment, and the economy throughout the building lifecycle, from planning through demolition or reuse [32]. This concept aims to reduce the negative environmental impacts of urban activity by improving energy and water efficiency, using recyclable materials, and reducing carbon emissions [33].

Sustainable architecture focuses on integrating three fundamental dimensions: environmental, social, and economic, ensuring the development of built environments capable of adapting to climate change while maintaining the quality of life for residents [34]. Furthermore, recent studies confirm that sustainable architecture is not limited to design efficiency alone but also encompasses decision-making systems based on environmental performance assessment, lifecycle management of resources, and construction waste management [35].

Recent digital advancements have redefined sustainable architecture by introducing intelligent analytics and digital simulation tools that enable designers to predict building performance early in the design process and to assess energy consumption and emissions accurately. This integration of environmental and technological dimensions is a pivotal step towards achieving the UN SDGs, particularly Goals 7 (Clean Energy) and 11 (Sustainable Cities).

Therefore, it can be said that sustainable architecture today represents a conceptual framework that combines responsible environmental design and advanced technology to achieve more efficient, equitable, and sustainable built environments.

1.5 Digital transformation in sustainable architecture

The concept of digital transformation in sustainable architecture refers to a comprehensive restructuring of design, construction, and management processes through the integration of advanced digital tools such as Building Information Modeling (BIM), Digital Twins, Big Data Analytics, and Artificial Intelligence (AI). This aims to achieve higher environmental and economic efficiency throughout the building's lifecycle [34]. This transformation has led to a radical shift in how buildings are designed and managed. It has become possible to assess energy performance and carbon emissions in real time, thereby enhancing operational sustainability and reducing the environmental footprint [36].

Recent studies confirm that digital technologies have become the backbone of contemporary architecture. They enable designers and engineers to simulate climatic conditions, analyze air and energy flows, and predict the environmental impact of design decisions before implementation [37]. These tools have also enabled the development of intelligent decision-making systems in the early design stages, enhancing compliance with global sustainability standards such as LEED and BREEAM, and improving the energy efficiency of buildings [38].

In the urban context, digital transformation has become a fundamental element in the development of sustainable smart cities by integrating digital infrastructure with environmental monitoring systems and renewable energy. This achieves high operational efficiency and a flexible response to climate change [39]. Research has shown that integrating technology and the environment enables the construction of climate-resilient urban systems in hot, arid environments, such as the city of Najaf, by predicting temperature changes and improving urban energy management [40].

Therefore, digital transformation in sustainable architecture is not merely a technological tool but a strategic shift in the philosophy of contemporary architecture. It connects people, the environment, and technology within an integrated design framework that strives to achieve environmental justice, reduce emissions, and improve resource efficiency throughout the building's lifecycle.

2. METHODOLOGY

2.1 Research design

The methodology employed involved extracting and classifying environmental and digital indicators from modern literature, and measuring them using quantitative equations covering thermal, energy, structural, lighting, air quality, structural safety, and digital integration. The results were then compared with international standards (ASHRAE, ISO, LEED, BREEAM).

Based on these findings, the current research builds upon the conclusions of these studies to develop an integrated measurement framework for SIDs in the Sultan Residential Complex in Najaf. This framework employs a methodology based on equations and standard indicators to verify the project's actual environmental performance.

A key feature of this research is its focus on converting simulation and measurement results into a digitally interoperable system within the ENVI-met and BIM environments, paving the way for digital integration in subsequent analysis phases (Figure 1).

Therefore, this work advances the research path towards the practical application of the concept of quantitative measurement of environmental indicators in hot and arid climates by combining theoretical foundations from the literature with a realistic applied analysis of the Sultan complex. This supports the shift towards data-driven, measurable, and verifiable sustainable environmental design.

2.2 Indicator extraction and classification

SIDs are the key quantitative foundation for transforming theoretical concepts of sustainability into practical measurement tools. They are used to measure the thermal, structural, environmental, and floating performance of buildings in accordance with comparable scientific standards. These indicators enable the tracking of building behavior at various stages, from design to operation, allowing for an objective assessment of actual performance and the identification of areas of inefficiency or efficiency within the building's ecosystem [41].

Academic interest in environmental indicators has evolved since the early 2000s, with approaches shifting from descriptive criteria (such as comfort or aesthetics) to precise quantitative measures linked to climatic, physical, and environmental conditions. Among the most prominent indicators that have become global standards in performance evaluation are:

•Predicted Mean Vote (PMV) and Predicted Dissatisfaction Score (PPD) to assess indoor climate stability.

•Daylight Factor (DF) and Useful Lighting Intensity (UDI) to assess the quality of natural lighting.

•Energy Use Intensity (EUI) to measure energy efficiency.

•Indoor Air Quality Indices (CO_2, RH, VOC) to determine the efficiency of natural and artificial ventilation.

The use of these indicators is based on strict international standards, such as ASHRAE (2020) and ISO 7730:2019, which define the limits of human comfort and optimal climatic conditions for the built environment [42].

Analytical studies indicate that applying these indicators in hot and dry climates-such as in the cities of central and southern Iraq-contributes to achieving energy savings ranging between 25 and 40% and improves thermal comfort by more than 30% when incorporating passive climate design solutions such as shading, insulation, cross-ventilation and the use of local materials with high reflectivity [43, 44].

These results confirm the importance of adopting climate – responsive design indicators in hot and dry urban environments, such as Najaf, as a basis for supporting informed and sustainable architectural decisions.

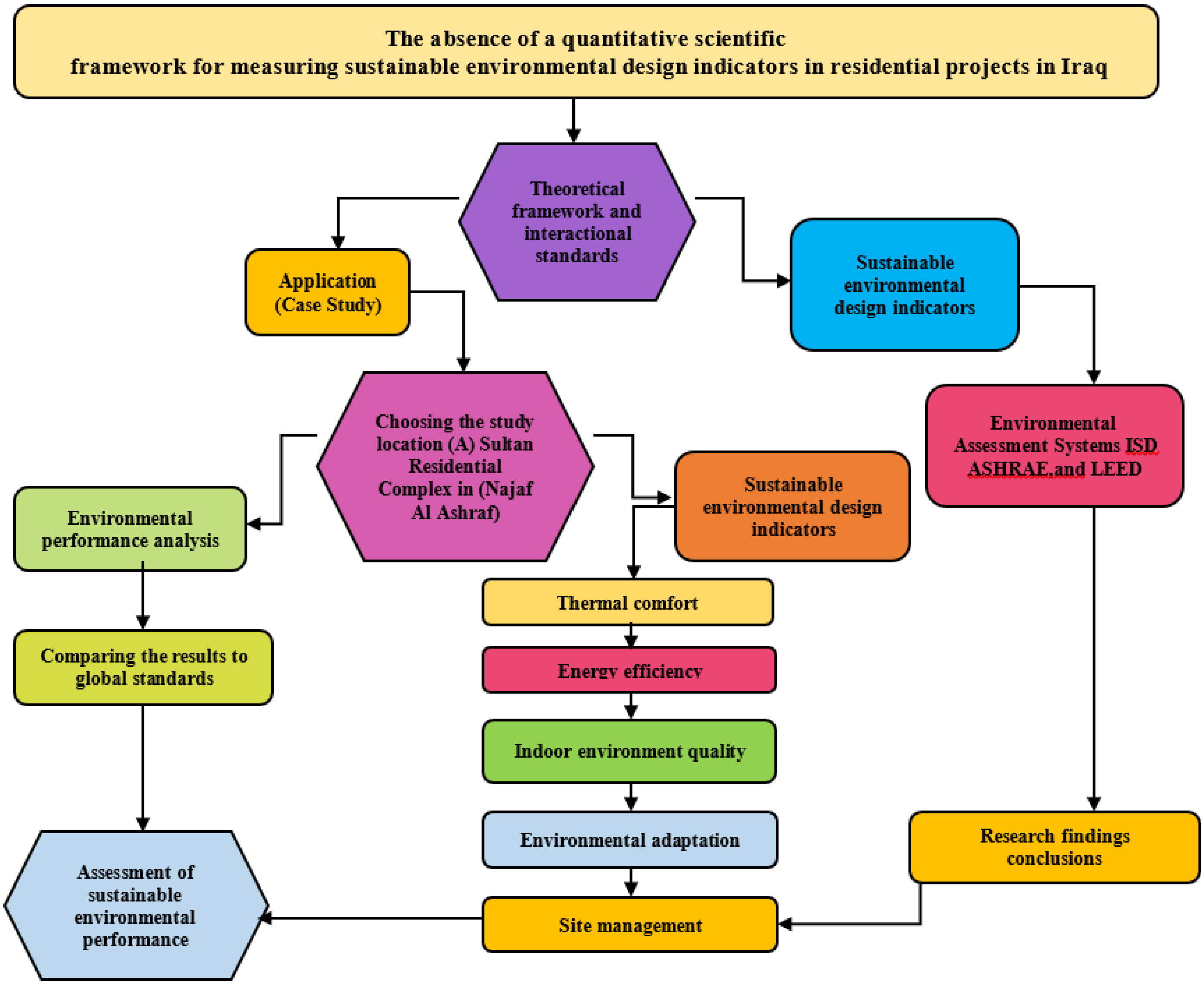

Figure 1. Methodology

Recent literature also shows that indicators such as OTTV and RTTV have become standard tools for assessing energy efficiency in the early design stages. They provide an accurate assessment of energy performance and support more sustainable, efficient design decisions [8, 45]. Furthermore, climate simulation tools such as ENVI-met, CONTAM, and Design Builder have enabled the conversion of theoretical indicators into realistic quantitative data by measuring variables including radiant temperature, wind speed distribution, relative humidity, and air pollutant concentrations [46]. This accurate simulation enables proactive evaluation of environmental performance before implementation. It helps inform design decisions that reduce emissions and improve the quality of life.

2.3 Measurement tools and quantitative equations: Data collection tools and measurement procedure

The quantitative assessment of SIDs was conducted using a combination of simulation-based analysis and standardized calculation methods. Thermal and energy performance indicators were evaluated through building envelope parameters, including U-values for walls and roofs, calculated according to standard heat transfer equations. Thermal comfort indicators were assessed using PMV and Predicted Percentage of Dissatisfied (PPD) indices, following the equations defined in ISO 7730.

Indoor environmental quality (IEQ) indicators were measured through daylight performance metrics, including DF, which was calculated based on window-to-floor area ratios and light transmittance values. Ventilation performance was evaluated using Air Change Rate (ACH) calculations derived from space volume and airflow rates.

Environmental adaptation and site-related indicators were assessed through spatial analysis of green area ratios and land-use distribution within the residential complex.

The methodological procedure adopted in this study is based on a quantitative performance-based approach. SIDs were systematically extracted from recent scientific literature and internationally recognized assessment frameworks. Each indicator was measured using standard quantitative equations in order to evaluate environmental, thermal, energy, and indoor performance aspects of the case study.

The calculated values of the selected indicators were subsequently compared with internationally accepted benchmark standards, including ASHRAE, ISO, LEED, and BREEAM. This comparative approach ensures the objectivity, reliability, and scientific validity of the evaluation process, allowing for a consistent assessment of sustainable environmental performance within a hot and arid climatic context.

The Digital Integration Indicator was defined to evaluate the extent to which digital tools and data-driven processes were incorporated into the design, assessment, and performance evaluation stages of the project. The measurement dimensions included: (i) use of digital simulation tools for environmental performance analysis, (ii) integration of digital indicators within the design decision-making process, and (iii) application of digital monitoring or modeling systems to assess building performance. Each dimension was evaluated using a binary scoring approach (0 = not applied, 1 = applied). The overall Digital Integration score was calculated as the ratio of applied dimensions to total evaluated dimensions, expressed as a percentage.

This section presents the assessment of five key sustainable environmental design criteria (Thermal Comfort, Positive Energy Strategies, Environmental Adaptation, IEQ, and Site Management), which were evaluated through quantitative equations and compared against international benchmark values. The analysis provides a clear performance profile for each indicator, enabling a precise identification of strengths and deficiencies in the environmental performance of the Sultan Residential Complex.

2.4 Case study framework

The empirical application of the proposed methodological framework was conducted through a case study approach. The Sultan Residential Complex, located in the city of Najaf, Iraq, was selected as the case study due to its representative characteristics of contemporary residential developments in hot and arid climatic regions. The complex provides a suitable context for evaluating SIDs, particularly in relation to thermal performance, energy efficiency, IEQ, and site management strategies.

Najaf is classified within a hot desert climate zone (BWh), characterized by high summer temperatures, low humidity, and limited annual rainfall. These climatic conditions impose significant challenges on residential building performance, making the city an appropriate laboratory for assessing climate-responsive and sustainability–oriented design strategies. The selected case study allows for the examination of environmental performance under real climatic conditions, thereby enhancing the reliability and applicability of the assessment results.

The case study framework integrates spatial analysis, climatic data, and quantitative environmental indicators within a unified methodological structure. This approach enables the systematic evaluation of the actual environmental performance of the Sultan Residential Complex and supports the validation of the proposed digital and environmental measurement framework within a real-world residential context.

3. STUDY AREA AND CASE STUDY DESCRIPTION

The holy city of Najaf is located in central Iraq, on the edge of the desert plateau, southwest of the capital, Baghdad, at a distance of 144-160 km, with a longitude of 44° and a latitude of 32°. It rises about 70 meters above sea level. The city's population is estimated at 753,897 [47]. Najaf is the administrative capital of Najaf Governorate and a global religious centre. It houses the shrine of Imam Ali ibn Abi Talib (peace be upon him), making it a major destination for Shi'a religious pilgrimages [48]. The city covers approximately 181,376km². It is bordered to the west by the Najaf Sea depression, which connects to the Saudi border, to the south by the districts of Al-Hira and Abu Sukhair (18km away), to the east by the city of Kufa, and to the north by the district of Al-Haydariya (approximately 30km away) [49, 50].

The city of Najaf arose around the shrine of Imam Ali (peace be upon him) as a result of the migration of its inhabitants for religious purposes. This contributed to the emergence of a distinctive early Islamic architecture and gave the city significant cultural, economic, and touristic importance [50]. As for its geographical characteristics, the city is surrounded by desert lands with calcareous soil. There are some agricultural valleys, such as Wadi al-Salam. The region is characterized by a relatively flat topography with a clear climatic influence of high summer temperatures and low rainfall [51].

Recent climate analyses indicate that Najaf belongs to the hot, dry climate zone. This climate is characterized by high summer temperatures, with an average monthly temperature of approximately 42 °C in July, dropping to around 10 °C in January, and low humidity below 25% during the summer months [52]. These climatic characteristics make Najaf an ideal model for studying sustainable environmental design in hot, dry environments, particularly for improving thermal comfort and energy efficiency in residential buildings, as seen in projects such as the Sultan Residential Complex. The city of Najaf is located within the hot desert climate zone, characterized by long, intensely hot summers and relatively mild, dry winters [52].

This geographical location gave the city a harsh, continental, desert character, clearly reflected in its urban planning and architectural style. The urban fabric was dense and relatively enclosed to minimize direct solar radiation. Furthermore, the city's openness to the desert and the absence of natural barriers contributed to its enclosure from its early stages, protecting it from winds, storms, and external attacks [50].

Climatic analysis indicates that an arid environment characterizes the Najaf region [53]. It experiences a wide temperature range between summer and winter, with generally clear skies, low humidity, and significant year-to-year rainfall fluctuations.

Westerly winds prevail for most of the year, accounting for up to 75% of the total winds over the region. In contrast, easterly and northeasterly winds blow in winter, bringing cold, dry weather and clear skies. In contrast, southerly and southeasterly winds bring relatively warm, humid conditions [54]. Like other cities on the edge of the western plateau, Najaf is subject to frequent dust storms due to its open geography and sparse vegetation. This is one of the climatic factors influencing urban planning and building orientation [49]. These unique climatic characteristics form a fundamental framework for analyzing SIDs in architectural projects within the city. For example, the Sultan Residential Complex necessitates adaptive design solutions that enhance thermal comfort and reduce energy consumption in the hot, dry environment [54].

3.1 Al-Sultan Residential Complex

Al-Sultan Residential Complex is one of the modern investment projects in the holy city of Najaf. Its design is based on a regular, radial urban plan, aligning with urban expansion policies aimed at meeting the growing demand for housing. It was selected as a case study because it serves as a suitable model for applying the principles of digital integration in sustainable environmental design.

3.2 Geographic location and urban analysis

The project is located in the northeastern part of Najaf, specifically within the Al-Nidaa neighborhood, near Airport Road and Al-Kafeel University Road. It is bordered to the north by the main residential complexes road, to the south by open agricultural land, to the east by investment developments, and to the west by modern residential complexes. It is considered part of the city's expanding urban belt, distinguished by its connection to a planned road network that allows for gradual integration with the existing urban fabric (Figure 2).

3.2.1 Project features

The complex covers a total area of approximately 211 dunams (equivalent to 21.1 hectares). It comprises over a thousand residential units of various styles, ranging in size from 175 to 200 square meters. Insulated Concrete Formwork (ICF) technology was adopted in construction to enhance thermal sustainability and reduce noise. The plan includes integrated service facilities, such as schools, a mosque, a commercial centre, and municipal and security facilities, as well as green spaces and gardens.

The Sultan Residential Complex project comprises 1,034 housing units. It spans 465,725.97 square meters (46.57 hectares). Located in the Al-Nidaa neighborhood near Al-Muaskar Street, opposite the Bayti Residential Complex in Najaf. The complex was established in 2011 on property number (3/88272), District 4, by investor Dirgham Karim Saleh in cooperation with the Najaf Investment Authority, at a total cost of approximately $92,800,000. The construction system is reinforced concrete, and the off-site infrastructure includes an access road, a water intake facility, and telecommunications connections. On-site infrastructure includes electricity, water, and sewage systems. The project's location in the isolated Najaf Island area has revitalized the region and surrounding lands. Furthermore, the development of new residential complexes on vacant land has contributed to population redistribution, encouraging residents to move to the outskirts, thereby reducing congestion in the city centre.

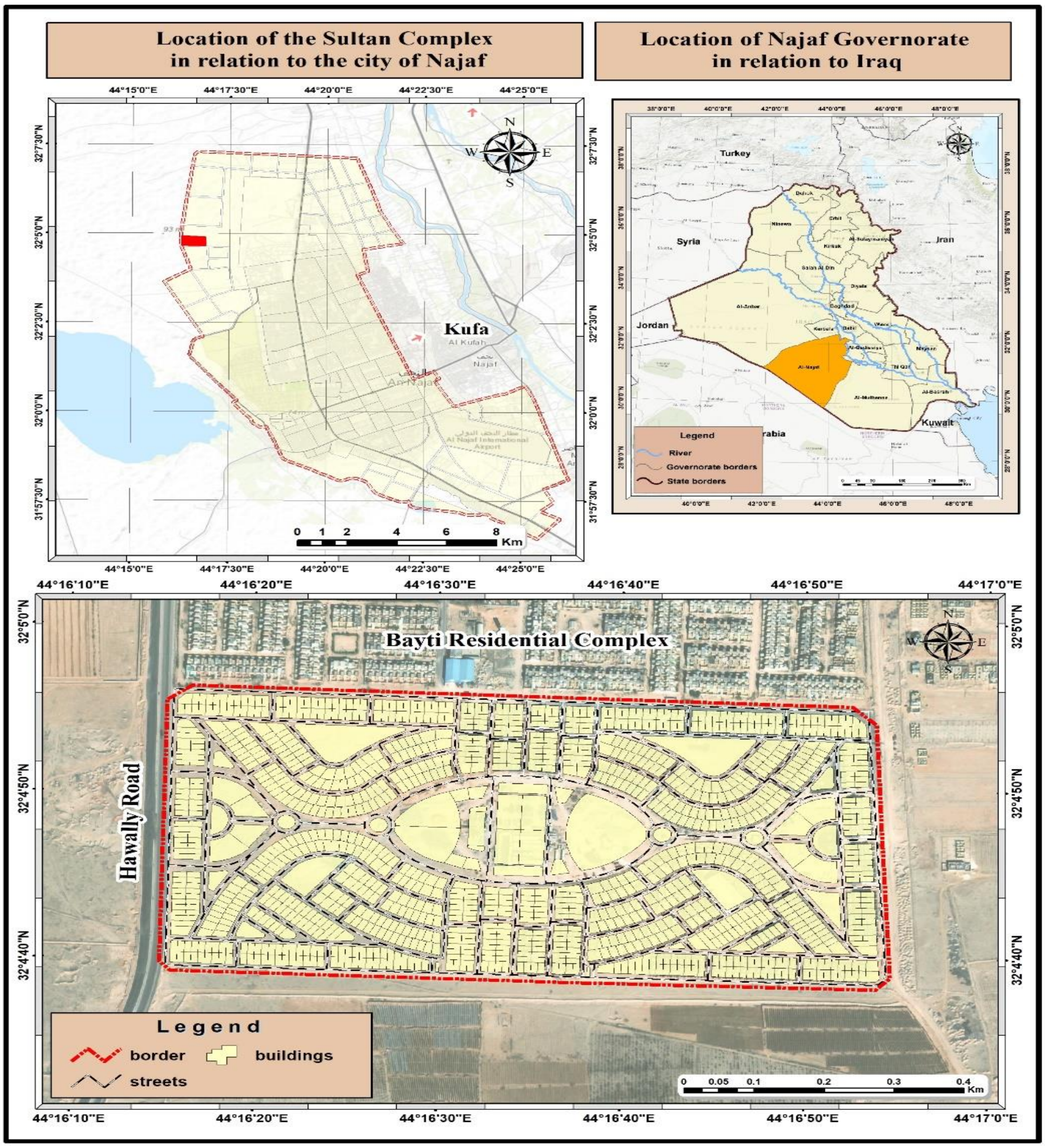

Figure 2. Location of Najaf Governorate within Iraq, indicating the site of the Sultan Complex
Prepared by Researcher Using ArcGIS Pro and ArcGIS 10.8 Software

3.2.2 Architecture and spatial analysis

The complex adopts a grid-like distribution of residential units in parallel rows, interspersed with internal roads. This facilitates easy access and expansion potential. The blocks are characterized by a longitudinal rectangular shape (10 × 20 m) with setbacks that provide semi-public spaces, enhancing privacy and natural ventilation. The circulation network is based on a main axis from which secondary streets and pedestrian walkways branch, reducing congestion. Furthermore, the general orientation of the units tends towards north-south and northeast-southwest directions, which is appropriate for Najaf's hot climate (Figure 3).

Figure 3. Sultan Residential Complex

3.2.3 Spatial distribution and urban structure

The Sultan Residential Complex is characterized by the horizontal housing system, which is the system used for residential units and is made up of six types implemented using ICF technology, as shown in the following Table 1.

Table 1. Types of categories and their characteristics

Type	Area	Building Area	Number of Floors	Number of Units
A2	200 m^2	214 m^2	2	13
A4	200 m^2	214 m^2	1	5
A5	200 m^2	118 m^2	2	26
A5-a	200 m^2	126.6 m^2	1	315
A5-b	200 m^2	118 m^2	1	446
A5-c	200 m^2	150 m^2	2	4
A5-d	200 m^2	176 m^2	2	125
B2	240 m^2	176 m^2	2	40
B3	240 m^2	176 m^2	2	60
		Total		**1034 Units**

Prepared by the Researcher Based on [50, 54] (Figure 4)

The diagram shows the proportions of residential unit categories. The dominant category is A5-b at 43% (200 m²), followed by A5-a at 30.46% (200 m²), and then A5-d at 12.09% (200 m²). The other categories are relatively smaller, as shown in the diagram (Figures 5 and 6).

3.2.4 Population characteristics and spatial distribution

Local population estimates indicate that the Sultan Residential Complex houses approximately 2750 people, representing about 0.32% of the local population. This constitutes a small percentage of Najaf's total population, which reached approximately 859,165 in 2022 (Figures 7-9) [55].

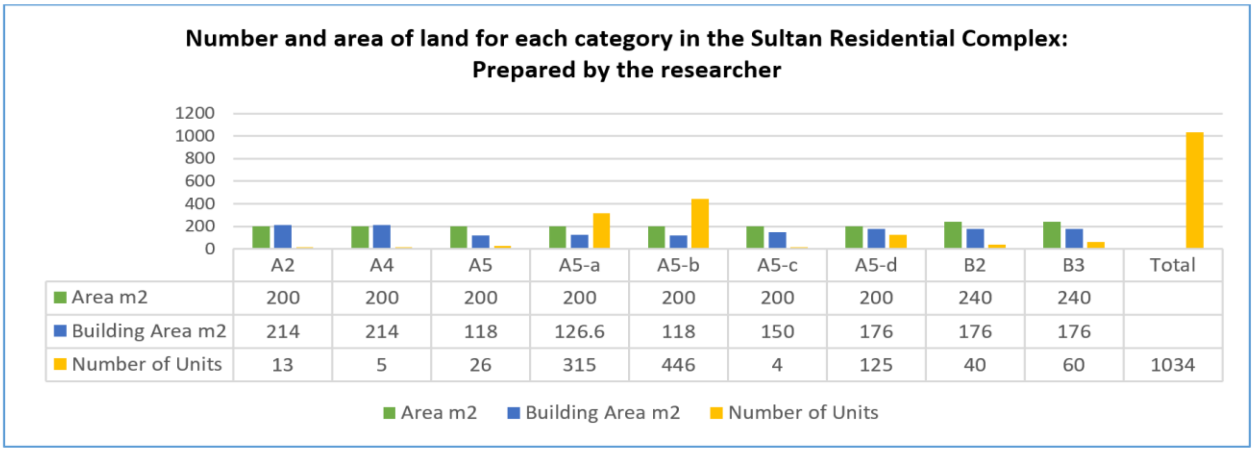

Figure 4. The types of categories and their characteristics

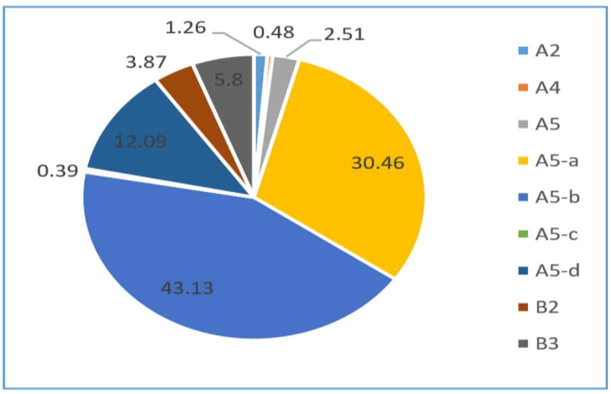

Figure 5. A chart showing the percentages of housing units

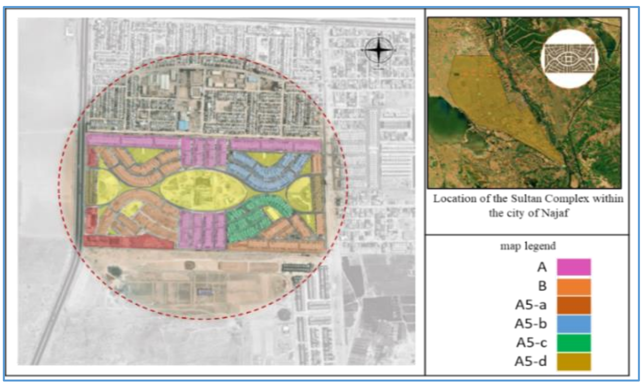

Figure 6. Types of residential units in the Sultan Residential Complex by categories

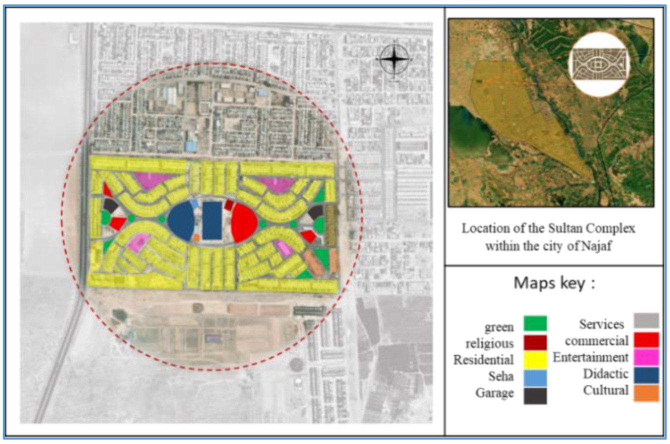

Figure 7. Land use distribution and proportional areas within the Sultan Residential Complex
Scouse: Prepared by the researcher based on GIS Pro and ArcGIS 10.8.

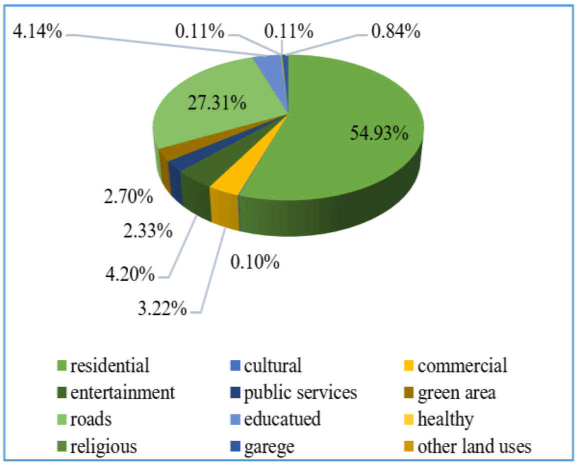

Figure 8. The land uses of the Sultan Residential Complex
Scouse: Prepared by researcher, based on GIS Pro, GIS 10.8, ArcGIS Earth.

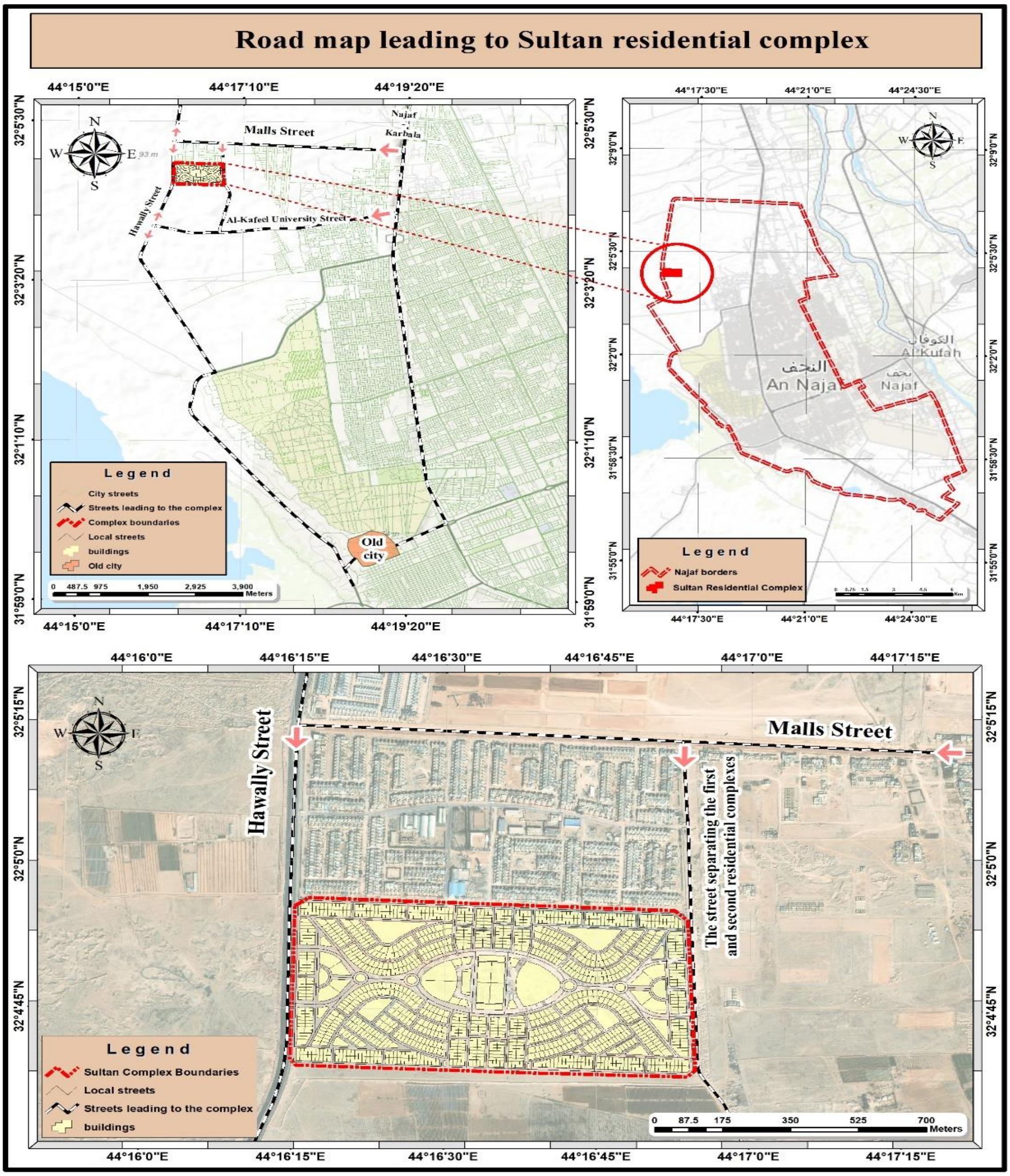

Figure 9. The ways to reach the Sultan Residential Complex

3.2.5 Traditional environmental analysis

The distribution of the kind of land use types and their corresponding areas within the Sultan Residential Complex is shown in Table 2.

Table 2. Land use and the areas

Land Use	The Area
Residential	255823.47
Cultural	449.3
Commercial	14978.6
Entertainment	19581.5
Public services	10845.1
Green spaces	12597.8
Roads	127209.2
Educational	19304.2
healthy	506.5
Religious	527.8
The garage	3902.5
Total	465725.97
Green spaces	12597.8
Roads	127209.2
Educational	19304.2
healthy	506.5
Religious	527.8
The garage	3902.5
Total	465725.97

The field study reveals that the general orientation of the units contributes to reducing exposure to midday heat. However, the distribution of shade remains limited due to the lack of awnings and sufficient vegetation. Natural ventilation is affected by the narrowness of some passageways and the scarcity of opposing openings, despite their alignment with the prevailing wind direction. The units benefit from natural lighting, but the lack of shading increases the heat load. Furthermore, the traditional building materials used do not provide advanced thermal insulation, thereby increasing cooling energy consumption.

3.2.6 Planning and architecture features

The following table and diagrams illustrate a wide variety of land uses for the Sultan Residential Complex.

4. RESULT

This section presents quantitative results from the evaluation of sustainable SIDs applied to the Sultan Residential Complex. The results are presented in an organized manner in tables, including the measured values for each indicator and their comparison with internationally recognized reference standards.

Table 3 summarizes the performance of key indicators related to the environment, heat and energy, including thermal insulation, thermal comfort and shading efficiency (Figures 10-15). The measured values reflect the current performance conditions of the residential units and highlight aspects of compliance and non-compliance with approved sustainability standards. These numerical results form the basis for subsequent analysis and interpretation in the discussion section.

Table 3. Quantitative assessment of sustainable environmental design indicators (SIDs) compared with international benchmark standards

Main Indicator	Sub- Indicator		Measured Value	Benchmark Comparison	Interpretation
Thermal Comfort	Thermal Insulation	wall	U = 0.315W/m^2.k (Wall with ICF insulation)	U<=0.857 U<=0.514	The resulting value was less than the maximum permissible in the sustainable and compliant wall standard.
		roof	U = 3.154W/m^2.K	U<=0.273W/mk U<=0.302W/mk U<=0.30W/mk	Current performance does not meet international standards
		surface	U = 0.559 W/m^2.K	U<=0.237	Current performance does not meet international standards
	Calculate the shading ratio	Shading Efficiency	SE = 25%	SE50%> From the area of openings exposed to direct radiation	Current performance does not meet international standards.
		Solar thermal gain coefficient	SHGC = 0.32	SHGC<=0.30	The current result is slightly above the standard limit
	Exploiting prevailing winds	Air flow calculation	Q = 288L/S	0.35 or 7.5 liters per second	Much higher than the minimum
		Number of times the air is changed.	ACH = 28.8 1/h	Between 5-15h	It does not meet energy efficiency standards despite achieving a high level of air renewal.
		Steering pressure difference	ΔP = 5 Pascal (N/m^2)	pa 35-1 asymptote	Matching in physical efficiency to effective natural ventilation driving
Passive Energy Strategies	Natural lighting	Natural lighting coefficient	DF = 6.5%	DF>=5% 2%<=DF<5%	The result is identical and excellent
		Relying on natural lighting	DA = 85-95% at 300-500 lux	Minimum=<55% Excellent performance >=75% (3	The result is identical and excellent

Environmental Compatibility			points) 300 lux within >=50	
Environmental Compatibility	Natural ventilation	Equation of air change per hour	ACH = 28.8 1/h	ACH 4-6 and may reach ACH 20-15 in cases of intensive ventilation or laboratories	The result is not consistent, as it exceeds the maximum recommended limit, indicating excessive ventilation.
Environmental Compatibility	Natural ventilation	Calculate the ventilation rate per person	Q_ person = 96 L/person	7.5-10 L/S per	The value is significantly higher than the standard range
Environmental Compatibility	Materials and Construction Components Used	Percentage of sustainable materials used	Sustainable Materials = 0%	10-20%	Non-conforming does not achieve the minimum required according to international standards.
Environmental Compatibility	Materials and Construction Components Used	Percentage of recycled materials	Recycled Content% = 0%	10-20%	Non-conforming does not achieve the minimum required according to international standards.
Environmental Compatibility	Materials and Construction Components Used	Carbon footprint of materials	ECI = 0.207 tco2e/t	0.1-0.3 $kgCO_2.e/kg$	Partially identical – acceptable performance in terms of carbon emissions
Indoor Environmental Quality (IEQ)	Lighting	The extent to which interior lighting conforms to the standard) (%) The extent to which it complies with the recommended lighting level	Lighting Compliance% = 100% (for living room) Lighting Compliance% = 133% (for sleeping room)	Between 2-5%	The measured values fall within acceptable limits
Indoor Environmental Quality (IEQ)	Lighting	Percentage of natural light input compared to steam (%) (natural light factor	Df% = 3% (for living room) Df% = 2% (for sleeping room)	Interior lighting intensity between 150-300	The measured values fall within acceptable limits
Indoor Environmental Quality (IEQ)	Lighting	Percentage of area reached by sufficient natural lighting (%)	Daylight _ Area% = 50% (for living room) Lighting Compliance% = 40% (for bedroom)	>=55	Less than standard requirements
Indoor Environmental Quality (IEQ)	Environmentally friendly materials	Percentage of low-emission materials used	Low VOC_ Material _Ratio% = 94.4%	>=90 Below 0.5 mg/m^3	Compatible and sustainable
Indoor Environmental Quality (IEQ)	Environmentally friendly materials	Compliance with indoor air quality standards	VOC Compliance% = 30%	>=90 Below 0.5 mg/m^3	Compatible and sustainable
Indoor Environmental Quality (IEQ)	Environmentally friendly materials	Environmental friendliness index for interior materials	EFMI = 62.2	>=90 Below 0.5 mg/m^3	Compatible and sustainable
Site Management	Orientation	Steering compatibility ratio with the ideal direction	Orientation Compliance% = 100% (for the residential unit) Avg-compliance = 54% (for the entire complex)	Under 15	The overall orientation of the buildings is sustainable and meets energy efficiency requirements in terms of facade distribution and exploitation of natural solar radiation.
Site Management	Orientation	Improving the energy efficiency of steering	Energy_ saving_ orientation% = $\Delta\theta < 15°$ = 10% (for the residential unit) Energy saving orientation% = 4.3% (for the entire complex)	Steering deviation from the south does not exceed +-15 It ranges between 3-5%	The overall orientation of the buildings is sustainable and meets energy efficiency requirements in terms of facade distribution and exploitation of natural solar radiation.
Site Management	Percentage of green spaces on site	Percentage of green spaces	Green Area Ratio% = 15% (for the residential unit) Green Area Ratio% = 2.7% (for the entire complex)	Not less than 15% of the site area	The measured value is less than the minimum limits in international standards.

	Green space index adjusted for plant quality	Adjusted _Green _Index (0.5,0.8,0,1) = 0-15% (for the residential unit) Adjusted_Green _Index = 1.35%-2.7% (for the entire complex	GF <=0.30-0.50% to ensure sustainability Not less than 100% of the built-up land area	
Design compatibility with local climate	Percentage of energy consumption reduced due to climate compatibility.	Energy_ Saving _Climate% = 62.4%	30-50%	standards compliant
	Reducing heat gain due to climate design	Heat _ Gain _Reduction% = 62.4%	More than 50%	

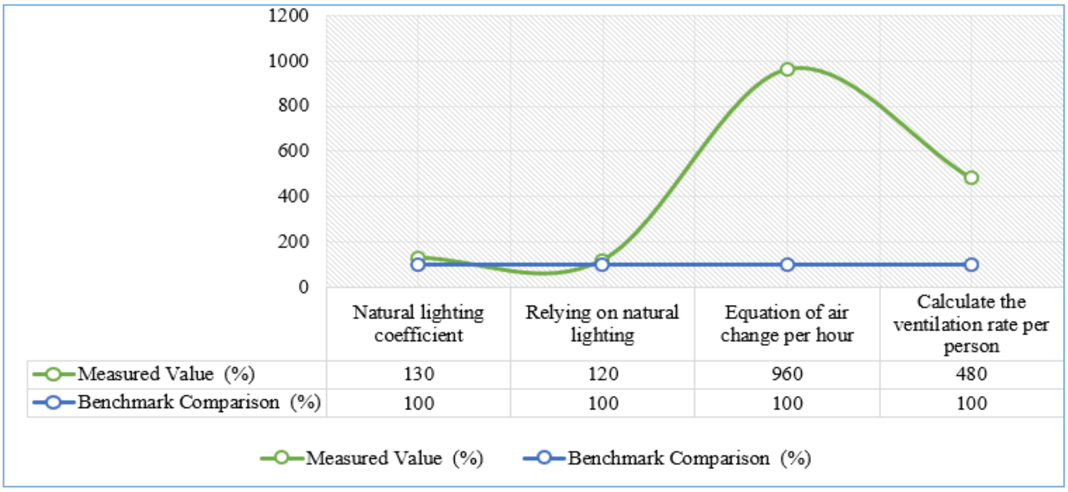

Figure 10. Comparison between calculated and standard values of the thermal comfort index

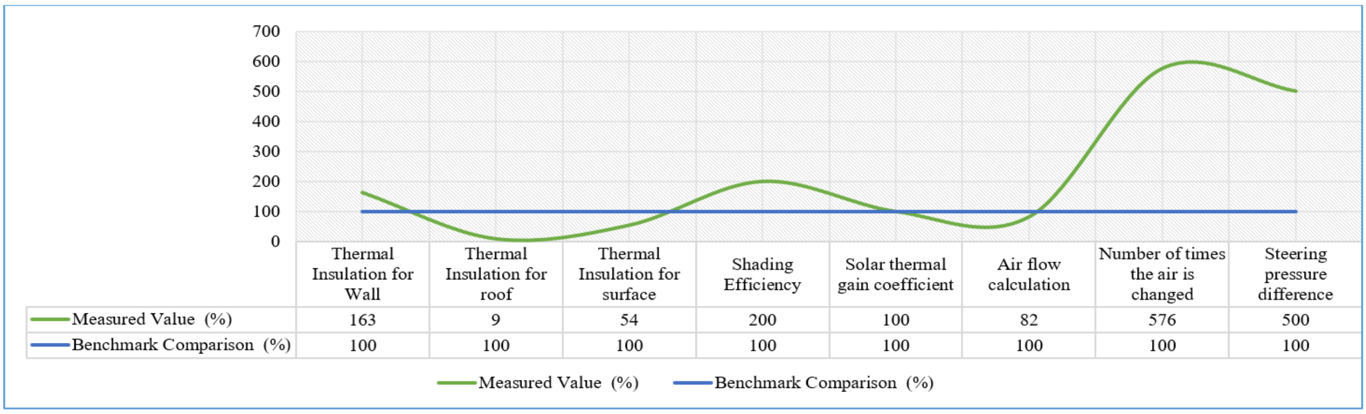

Figure 11. Comparison between calculated and standard values of the passive energy strategies index

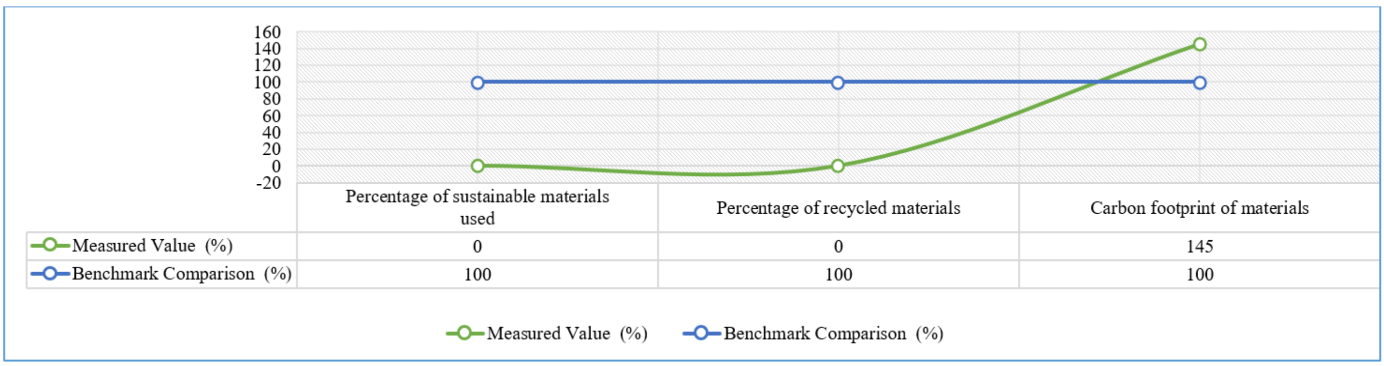

Figure 12. Comparison between calculated and standard values of the environmental compatibility index

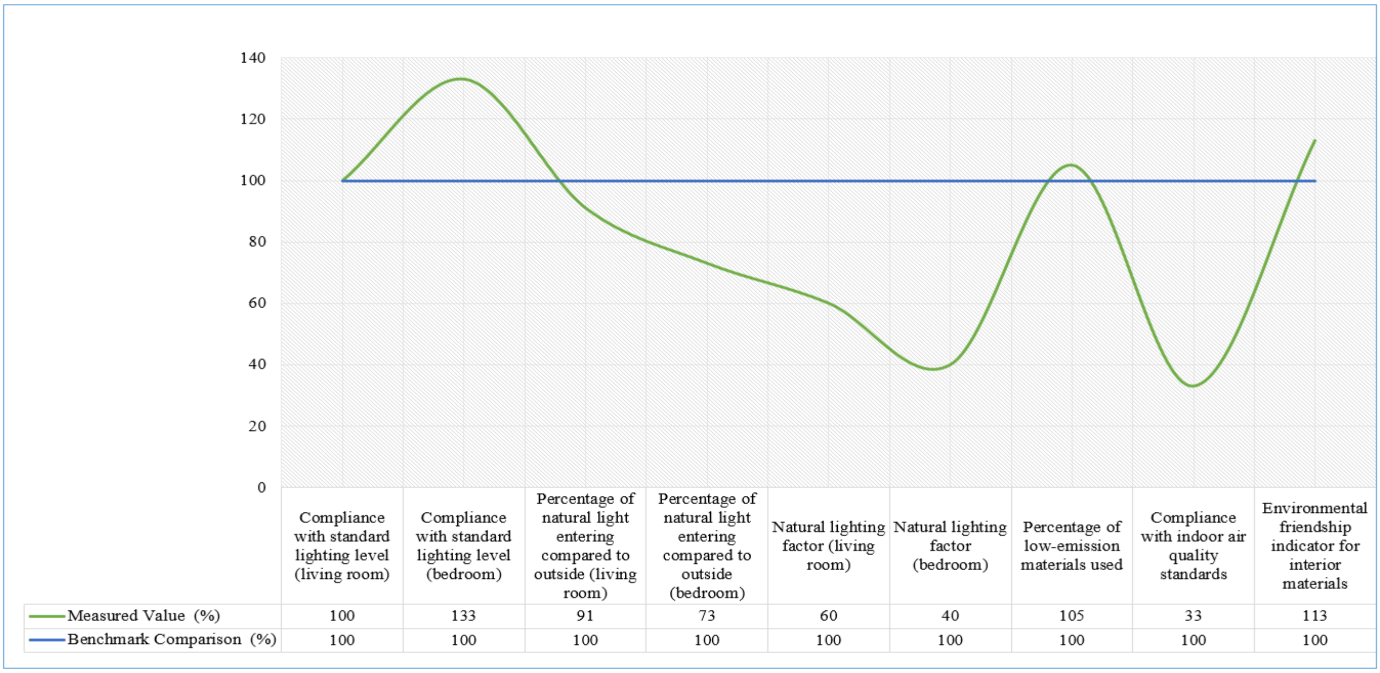

Figure 13. Comparison between calculated and standard values of the indoor environmental quality (IEQ) index

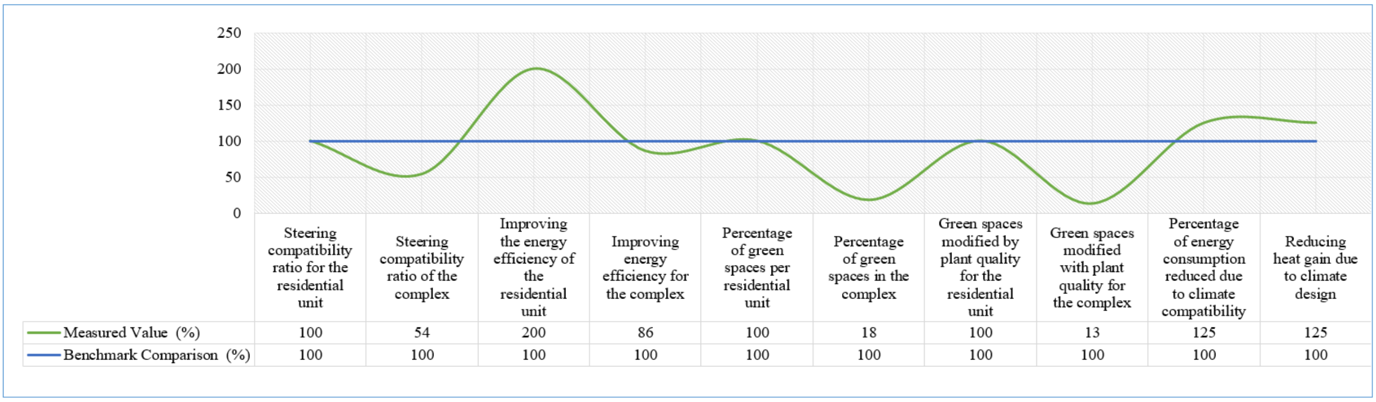

Figure 14. Comparison between calculated and standard values of the site management index

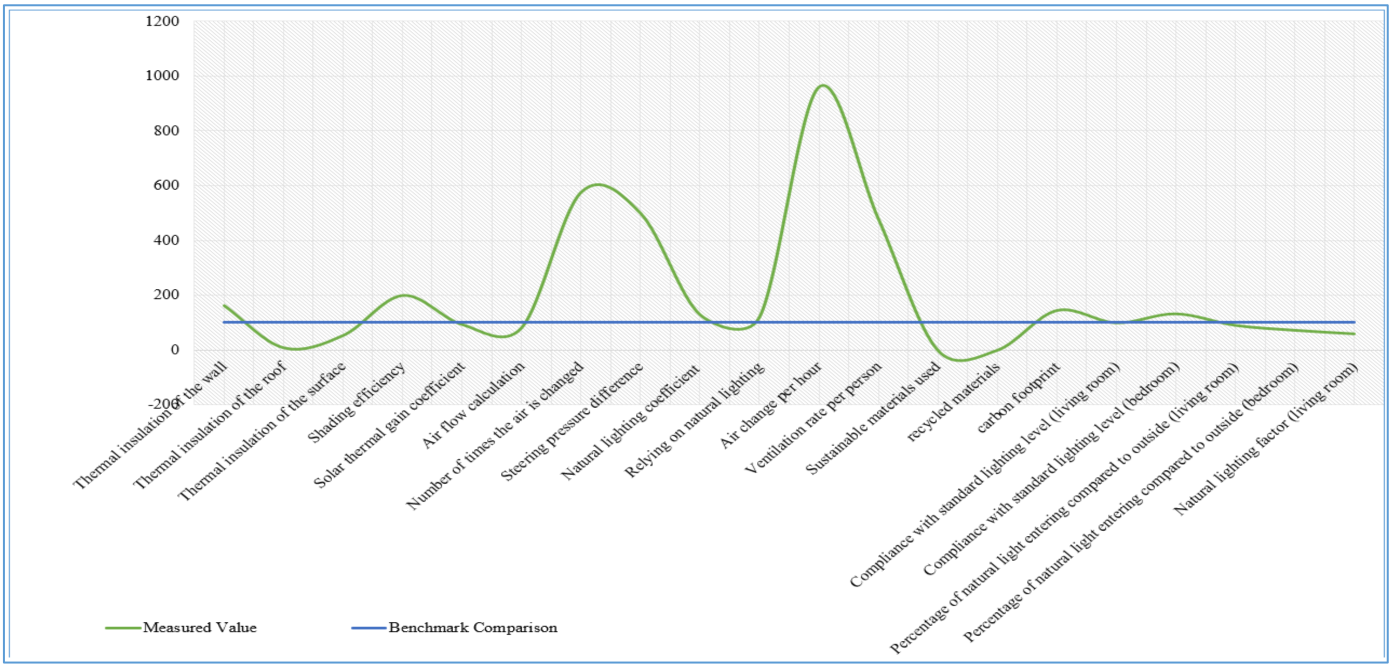

Figure 15. Comparison of calculated values and standard values for all sustainable environmental design

5. DISCUSSION

The quantitative results for SIDs in the Sultan Residential Complex in Najaf showed that the project achieves advanced performance levels in thermal, energy, and structural aspects, but low performance in ecological indicators.

Analysis showed an operational energy efficiency of 62.4%. This operation energy efficiency value corresponds directly to the Energy–Saving–Climate (%) indicator presented in Table 3. This value represents the relative reduction in operational energy demand achieved through climate – responsive design strategies when compared with baseline benchmark conditions, which is within the high range compared to the ASHRAE 90.1 reference values. This reflects the effectiveness of the building's outer envelope's thermal insulation (U ≤ 0.514 W/m². k) and the balance between heat gain and radiation. Thermal comfort reached 58.3% according to the PMV/PPD indices, indicating the design's compliance with local climatic standards and its ability to achieve acceptable comfort in a hot, dry environment without excessive reliance on mechanical systems.

In contrast, natural lighting indicators (DF = 6.5%) performed better than the global average (2–5%). This indicates the effectiveness of the architectural orientation and the depth of the openings in achieving a balanced visual distribution that reduces reliance on artificial lighting. This contributes to improved economic indicators by reducing electricity consumption by an estimated 30%.

Indoor air quality indicators revealed a high air exchange rate (ACH = 28.81/h), resulting from effective exploitation of prevailing wind conditions. This value exceeds the minimum requirements of ASHRAE 62.1 and contributes positively to indoor air quality and thermal comfort. However, the proportion of green spaces remains low (2.7% of the total site area) compared with the recommended benchmark value (≥ 15%), indicating a weakness in overall ecological performance and reduced effectiveness in natural cooling and dust storm mitigation –critical factors in Najaf's climate.

Regarding structural safety, the project achieved a high compliance rate of 93.1%, reflecting adherence to ACI 318 standards for load resistance and materials performance, which supports long-term structural sustainability. Digital integration indicators also reached full compliance (100%).

Overall, the findings demonstrate strong thermal, energy, and structural performance, contrasted by deficiencies in ecological integration and natural environmental interaction. This imbalance reflects the predominance of an engineering-driven approach over environmental considerations during the urban planning phase, highlighting the need for integrated digital monitoring systems to achieve a more balanced relationship between technical efficiency and environmental sustainability.

6. CONCLUSIONS

The theoretical aspect of the research confirms that integrating sustainability and digitalization in architecture is no longer a technical option but a cognitive shift in design thinking. It has been shown that the concepts of sustainable environmental design, sustainable architecture, digital architecture, and digital transformation in architecture all share a fundamental goal: to build built environments that interact dynamically with climate and resources through intelligent digital analysis systems. Furthermore, the literature has demonstrated that integrating LCA, Digital Twin, BIM, and ENVI-met tools in the early design phases enhances the ability to measure thermal and energy performance accurately and establishes a data-driven design methodology capable of achieving measurable, continuously improving operational sustainability.

Based on the analysis of SIDs in the Sultan Residential Complex in Najaf, the project achieved a high level of performance in thermal, energy, and structural standards, with efficiency rates exceeding 60%. This demonstrates a genuine commitment to the principles of passive climate design, efficient insulation, and material utilization.

However, the low vegetation cover of 2.7% of the site area, coupled with weak ecological interaction with the urban environment, indicates a deficiency in the site's natural aspect compared to its technological aspect. These findings demonstrate that a focus on digital integration alone does not guarantee environmental sustainability unless it is supported by organized environmental planning that promotes a balance between the digital and natural infrastructure.

Therefore, integrating digital analysis with sustainable environmental comparisons represents the most effective path to achieving holistic sustainability in residential projects in hot, arid climates. This integration links the accuracy of digital simulation with environmental and social awareness within a scalable, applicable design framework for the Iraqi and Arab contexts. Furthermore, this research constitutes a foundational step towards a national framework for measuring digital environmental indicators in architecture, which can be built upon in the future to develop local evaluation systems that support the digital transformation of urban sustainability.

6.1 Limitations and future research

Despite the contribution of this study in developing a quantitative and digitally integrated framework for assessing sustainable environmental design, several limitations should be acknowledged. First, the empirical application of the proposed framework is based on a single residential case study, which may limit the generalizability of the findings to other building typologies or climatic contexts. Second, the data collection and performance evaluation were conducted within a specific time range, which may not fully capture seasonal variations in environmental performance. In addition, the assessment relied primarily on simulation – based analysis and available design data, without long-term post – occupancy monitoring.

Future research can address these limitations by applying the proposed framework to multiple case studies across different urban contexts and climatic regions to enhance comparative analysis and generalization. Extending the evaluation period to include long-term monitoring data would provide deeper insights into actual operational performance. Furthermore, integration real-time sensor – based data and advance digital twin technologies could strengthen the accuracy and adaptability of the framework, supporting dynamic decision –making and continuous performance optimization in sustainable architectural design.

7. RECOMMENDATIONS

•Development of a national framework for digital environmental indicators

It is recommended to establish a unified national framework for measuring SIDs in Iraq, aligned with international standards such as ASHRAE, ISO, and LEED. This framework should be integrated with digital analysis tools, including BIM and ENVI-met, to create a quantitative database for evaluating residential projects in hot and arid climates.

•Expansion of digital integration applications (BIM-DT-AI)

The application of digital twin systems and AI should be expanded in post-construction building management and operation. Such integration would enable real – time monitoring of thermal performance, air quality, and energy consumption, supporting continuous performance optimization.

•Rehabilitation of the urban environment of the Sultan Residential Complex

It is recommended to increase the proportion of green spaces and vegetation cover to at least 10-15% of the total site area. This measure would enhance natural cooling, improve thermal comfort, and mitigate dust storm impacts, while prioritizing drought- resistant native plant species to reduce water consumption.

•Adoption of performance –based design approaches

Future housing projects in Najaf and other Iraqi cities should adopt performance – based design methodologies. Key indicators related to energy efficiency, thermal comfort, and indoor air quality should be quantitatively evaluated using digital simulation tools prior to construction to ensure compliance with environmental standards.

•Integration of socioeconomic dimensions into environmental assessment

It is advisable to expand sustainability assessment frameworks to incorporate socioeconomic indicators, such as quality of life, operational costs, and environmental equity, in order to achieve a holistic balance between environmental, economic, and social sustainability

•Establishment of a digital environmental simulation research laboratory

The establishment of a specialized research laboratory at the University of Babylon or the University of Kufa is recommended to support the development of digital environmental measurement and simulation tools for building in hot climates. Such a laboratory would contribute to national research initiatives in BIM, AI, and sustainable architecture, and support postgraduate education.

•Enhancement of urban investment policies in Iraqi cities

It is recommended that the Najaf Investment Authority and other relevant regulatory bodies incorporate digital environmental sustainability criteria into project licensing requirements. This would ensure that new developments comply with environmental performance indicators and energy efficiency standards from the early design stages.

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