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New approaches for sustainable & resilient processes and products of social housing development in the Arabian Gulf Countries

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New approaches for sustainable & resilient processes and products of social housing development in the Arabian Gulf Countries

Topic editors

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Editorial: New approaches for sustainable and resilient processes and products of social housing development in the Arabian Gulf Countries

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social housing, sustaibanility, urban resilience, housing process, housing product, housing development, Arabian Gulf Countries

Editorial on the Research Topic
New approaches for sustainable and resilient processes and products of social housing development in the Arabian Gulf Countries

In recent decades, the Arabian Gulf Countries have witnessed profound transformations of their social housing paradigms from the conventional approaches of generous built-up areas and urban sprawl designs to more environmentally, socially, and economically sustainable and resilient social housing. These transformations have been mainly initiated by the adopted local sustainable development and housing agendas in each country. With its 12 diverse articles, this Research Topic sheds light on these recent transformations from different perspectives with the aim of better understanding and documenting these new social housing approaches.

First, the lessons learned from indigenous housing and early social housing practices are discussed in two articles. In their study of the architectural typology of indigenous houses in Iran, Ghanbari et al. present valuable lessons extracted from the resilience of the indigenous homes by analyzing the adaptation they have undergone over time as a result of internal needs and exogenous changes. The study revealed the preserved architectural styles and design elements, especially house orientation, open plan, and natural ventilation. Regarding the early social housing experience, Assi's study discusses the degree of resilience of the pioneering social housing projects (*Shabiyat*) in the United Arab Emirates (UAE) and examined the notion of home mobility and how it is related to resilience through physical and non-physical spatial transformation and everyday practice. The study avails more understanding of the resilience of the *Shabiyat* and examines how they addressed the needs of Emirati society. This study offers some practical guidance for developing sustainable policies for future social housing projects.

Second, the assessment of social and cultural aspects of the current practices of social housing in the Arabian Gulf Countries are discussed in four articles, culminating in some valuable proposed solutions for the social housing process and product. Mohamed et al. offered an alternative approach for the design and delivery of national housing practices in the UAE to overcome the problems facing the current social housing practices regarding their appropriateness for family needs and socioeconomic challenges. The proposed approach relies on design flexibility and customization, a computational design strategy for facade optimization, and a prefabricated building method combining precast concrete systems with three-dimensional printing technology. In another study, Al-Ansari and AlKhaled conducted a critical analysis of the current social housing practices in Kuwaiti social housing neighborhoods in Jaber Al-Ahmed City. They examined the status of recent social housing projects in the city through evidence-based analysis of the decision-making processes and urban-architectural products. The study revealed the important sustainability aspects that remain in question in Kuwait.

In the third study, Lafi et al. analyzed the widespread modifications made by residents in social housing in Bahrain to identify the issues leading to such modifications. These include residents' need to modify their houses according to their lifestyles, which appeared in the guest room, the courtyard, and the interior divisions of the extended bedroom. Considering the revealed preferences of residents while designing future social housing projects in Bahrain helps create flexible units that satisfy the needs of the majority of residents while allowing for modifications at any time. Another innovative social housing typology is cohousing, as suggested by Yahia et al. They claim that the variety of societies in the Emirates with their various habits, experiences, and traditions endorse such a new housing typology. They discussed the socially and culturally challenging considerations of cohousing. The study concludes with some design guidelines for future cohousing in the UAE, considering the pillars of the local Estidama (sustainability) program, in addition to the role of architecture design. The study showed that future cohousing in the UAE is expected to enhance social interaction and contribute to sustainability in the long-term perspective.

Third, the environmental aspects of social housing design in the region and suggested innovative assessment tools and relevant enhancement recommendations are addressed in four articles. The issue of rising average temperatures in the UAE and the massive heat island agglomeration is addressed by Alkaabi et al., who explored the feasibility of using drone-captured three-dimensional thermal imaging to carry out thermal photogrammetric mapping of buildings and pedestrian spaces to monitor and classify heat rates based on building components. Furthermore, Salameh et al. examined the thermal effect of the variations in the height of housing buildings on the urban layout and canyons in the hot arid climate of the UAE. The study defined the best-performing configurations of housing urban forms with unified and diverse heights.

Another innovative study about thermal comfort in the housing built environment in the harsh weather context of the UAE, and the whole region, was undertaken by Alkaabi and Raza, who investigated the dynamics of the car cabin environment and driver comfort. The importance of the study is asserted by the fact that most residents in the UAE still heavily rely on private cars for commuting. Summer heat in the UAE was found to have a significant effect on drivers' perceptions of body fatigue, body heat, and eye fatigue. The research findings have implications for car cabin ergonomics and future thermal comfort research.

Fourth, in an interesting study about mitigating the impact of sandstorms through the urban landscape, El Amrousi et al. had an interesting look at the current labor housing projects in the UAE, which are usually characterized by grid-based compositions, simple facades, and block buildings positioned on the outskirts of cities. They found that Interventions from the community via the introduction of small garden stock have not only increased the sense of belonging and improved the urban fabric, but also reduced sand movement in the area. This is important in the Arabian Gulf region's desert environment, which gives rise to sandstorms. The study evaluated the amount and distribution of sand around a selected group of buildings in the Mussafah area of the city of Abu Dhabi, UAE, and put forward some enhancement recommendations.

Fifth, accessibility to neighborhood parks of social housing in the UAE is discussed in an interesting study undertaken by Alkhaja et al., who examine the impact of neighborhood parks as a key asset in mitigating the negative implications of extended lockdowns due to the spread of COVID-19. They focused on the provision of access to community parks via efficient routes through enhanced network connectivity. The study revealed that the current design and planning guidelines, implemented by the Department of Transport and Municipalities in the UAE, are overly descriptive with regard to how neighborhood parks are accessed; therefore, the study suggests a possible more evidence-based approach to policy development.

Finally, Hasanain and Nawari discussed the urgent need to accelerate the slow transformation of current housing designs into more sustainable forms in Saudi Arabia. They call for uniformity across jurisdictions to make sound and well-informed decisions about adopting and "enforcing" sustainability measures in social housing projects. To do so, they utilized the advanced capability of Building Information Modeling (BIM) and developed a BIM-based model to help facilitate green building certification in Saudi Arabia, which supports the country's sustainable vision of 2030.

Author contributions

KG: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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ORIGINAL RESEARCH
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Architecture Typology of Rural Plain Houses Based on Formal Features, Case Study: (Talesh, Iran)

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Housing is the most essential human need that in the past, rural houses have met this need well. Indigenous rural homes have undergone changes over time, some of which have been based on internal needs and needs, and some have been due to development and exogenous changes. One of the most critical steps to identify this type of change is the typology of indigenous homes; In this way, an essential step in the path of cognition, understanding and more coverage of this phenomenon is taken. Based on this, the present study intends to study and analyze the architectural types of houses in Talesh village, which originate from human nature, natural space and the bed in which they are formed. Therefore, to estimate the proportions and classification of the architectural plans of its houses, it is necessary to use a quantitative-qualitative research method. Mathematics is used in the *Python* programming language in data analysis. For this purpose, by selecting 150 samples of rural houses in the form of purposeful clusters and converting the created matrix from the dimensions and size of the plans to zero and one code, their similarity has been calculated. They are in close categories. Findings obtained by simulating the plans show that sloping roofs, building elevation, east-west orientation, porch, open plan and natural ventilation are common features in all indigenous houses. It is found in this area. Therefore, in general, the two architectural patterns in this area are one-story houses and Telar houses, in which high chair houses are a frequent type.

Keywords: typology, talesh rural houses, indigenous architecture, plan geometry, historic

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INTRODUCTION

Providing desirable rural housing in the country is an increasingly vital need (Raheb, 2016, 4). Today, forgetfulness and inattention to the architectural methods of the past have reduced the quality of rural housing. The study of indigenous houses as part of the great and fruitful treasure of the history and architectural culture of this land can make us aware of the economic and social conditions of the past. Cultural heritage has been passed on to future generations and has significantly impacted today's buildings. Indigenous housing is well aware of the originality of life and environmental potentials. Instead of ignoring the needs of life and fighting geographical variables, Coordination has been formed with it (Sartipipour, 2011, 3; Motevalian and Yeganesh, 2020.).

Undoubtedly, the native architecture of Gilan, as a manifestation of art and beauty in the rural sector, has unique features that today can be used and expanded in design and planning in the housing sector. Attention and extraction of these concepts and principles not only increase the

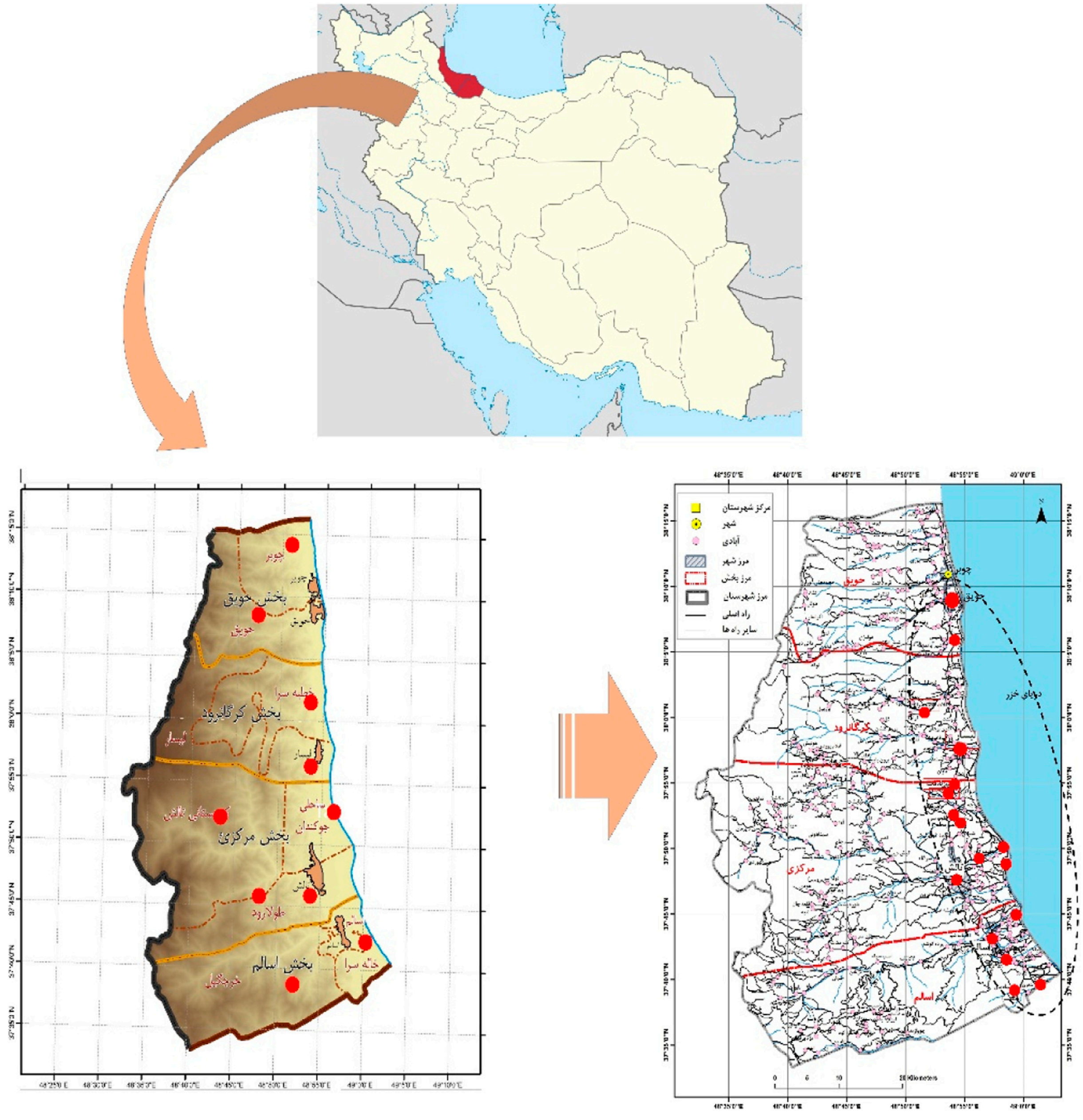


FIGURE 1 | Research trend chart, source: Author.

compatibility of residential buildings and structures with environmental and climatic conditions but also due to the creation and expansion of the cultural context of residents, is also effective in raising the quality of life (Yaran and Khoshbin, 2019, 16; Yeganeh and Kamalizadeh, 2018).

Studies show that a simple look at the past has led to traditional elements and has had detrimental consequences. A typology is an essential tool for abstracting these architectural patterns. Through a species- Comprehensive cognition provides access to abstract patterns of traditional architecture and the application in today's architecture (Mashhadi and Aminpour, 2018, 174; Yeganeh 2020). Typology, which is used in various sciences to better classify and recognize its phenomena, is a critical concept in architecture and urban planning and has been studied by many authors. In his famous work (Architecture Book), Vitruvius grouped different Greek buildings, including houses, temples, and public buildings. The houses were sorted according to their location in the city and village (Architects, 2005 104). In the contemporary period, many architectural researchers such as Aldorossi, Argan, Imonino, Krayer have addressed this issue (Memarian and Dehghani Tafti, 2018, 1; Yeganeh, 2017; Apoorva et al., 2018; Rodrigues et al., 2013; Rodrigues et al., 2014).

TABLE 1 | Classification of research done in the field of research.

Title	year	Author(s)	Discussion
Housing and architecture in Gilan rural community	1992	Brumbergeh, kristan	One of the most important features of rural architecture in this region is based on human physical and life. In this book, most of the houses have been paid for physical, social and economic properties
native housing in Gilan rural communities	1994	Khakpour, Mojgan	This paper deals with how to create rural housing.also a brief look at the physical development process of native architecture in gilan villages
extrovert architecture	2006	Memarian,GholamHossein	One of the writings that in general is the typology of rural housing.in this book, the architectural species of gilan, abyaneh and masouleh after field studies, collected and analyzed the samples from the perspective of context and single building
Musazadeh House)Gilan Rural Architectural Heritage), West Plain	2012	Taleghani, Mahmoud	In this book, in addition to being paid attention to an overview of gilan province in the execution style of architecture, a full investigation on a sample of rural houses in the western plain of gilan has been studied
The Orowa House: A Typology of Traditional Yoruba Architecture in ILE-IFE	2013	Cynitha, Adeokun	Studying the typology of vernacular homes in Nigeria.the spatial pattern and spatial organization principles have been extracted in these native houses by spatial syntax analysis
Species and Typology of Architecture	2014	Memarian, GholamHossein. Tabarsa, Mohammad Ali	In the study of the typology in architecture and offering different interpretations of it, it is concluded that type can be defined as a group of objects with common characteristics that define these properties depending on the interpretation made by it
Typology of Traditional Houses in Talesh City case study: khaleh Sara Villages57	2015	Hassanpour Lemaire, saeed	In this paper, for re - use of rural homes and continuity patterns, field observations and library studies have been used for the typology of Khaleh Sara's rural homes. Therefore, by investigating the physical elements and spaces in its homes, there are three common types in architectural architecture
Typology of Rural Housing in Gilan Province	2015	Tarkashvand, Abbas.raheb, ghazal	In this book, classification of native models of Gilan's rural housing is discussed and by relying on the local values of optimal housing design criteria in this province.in this study, there are four design patterns for future homes in plain areas
Typological Descriptions as Generative Guides for HistoricalArchitecture	2015	Stouffs et al. (2015)	This paper presents a descriptive language instruction approach to the production of historical architectural topology
Analyzing the concept of "species" in native housing and explaining an approach for classification of rural housing species in Iran	2016	Raheb, ghazal	This paper presents the traits that a typology of housing should possess.It also points out that species that have been formed in compliance with the surrounding environment will continue.Therefore, it can be considered as a genuine biological species
Clustering of architectural floor plans: A comparison of shape representations	2017	Raheb, ghazal	in this study, the simulation process in order to perform classification operation has been done using artificial intelligence in the Java programming environment.the results show that using a network matrix method has higher accuracy in sorting architectural patterns
Development of process and indicators affecting architectural typology with combining characteristic criteria (case example of historical monuments in Arak city)	2018	Mashhadi, Ali. Aminpour, Ahmad	In this study, the typology and introduction of its indexes has been studied. Research results introduce a combinatorial typology as the method that has the ability to review the process of achieving options and reproduce the species

In all studies in the world of architecture, species or "type" means a representative of a group of architectural organs with a physical aspect (architectural spaces, structures, decorations, materials, etc.) that with a specific mechanism, collection and categorization have achieved. The basis of this organization is based on common climatic elements, common geometric shapes, a common genetic code (genotype) and anything that can give the meaning of representation to identify other members of the group (Tusi Hoda and Iraj, 2019, 4). Accordingly, considering that the "classification system" typology is to express or want a series of

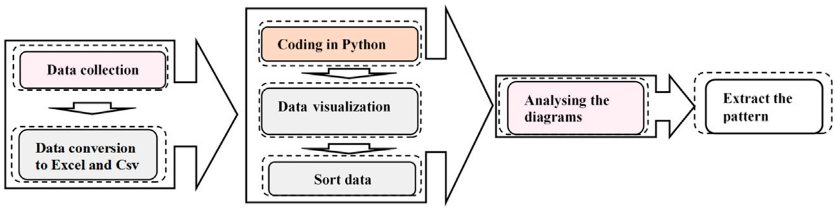


FIGURE 2 | Cosine similarity formula and Angle representation of analogy vectors by cosine distance method (Garcia, 2018, 9).

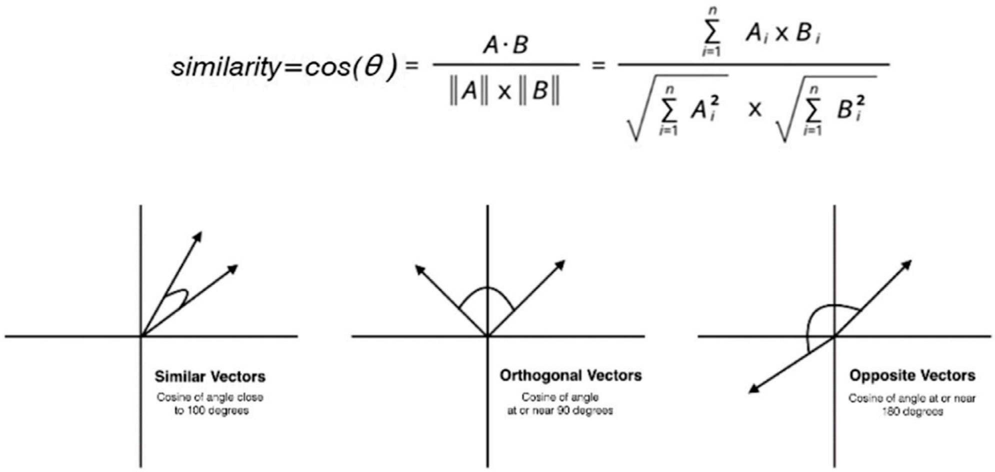


FIGURE 3 | Location of selected houses in Talesh city; Source: Author.

limited connections between phenomena. Recognition and correct classification of different types of architecture can be useful in better understanding the space, its protection and access to new design methods (Hassanpourrmarr, 2014, 117; Norouzi et al., 2021). Because rural housing has direct, direct and robust lines of communication with the culture of the masses and with their daily lives. These buildings were built by people who have used all their intelligence and capacity to build them and all the existing relationships between They have used them in making them (Bazen and Bromberje, 1986; Bromberjeh, 1991; Haji Ebrahim Zargar, 1999; Elsayed et al., 2014; Bayegi et al., 2018).

For this purpose, regarding the improvement of rural housing situation due to the prevailing diversity of rural settlements, which is affected by various factors, this breadth and diversity of housing construction methods in rural areas requires comprehensive and macro information and provides a classification. It is accurate and comprehensive. As one of the innovative methods, algorithms can collect this information in a short time and a reasonable computational volume and find an optimal classification that increases the chances of finding better performance (Mazandzani and Reza, 2009; Kasmaei, 2006; Al Qady and Kandil, 2014). Accordingly, the purpose of this study is to provide a practical and usable approach to the classification of indigenous housing based on form, form and case in Talesh plain villages. Indigenous people in the rural context of Talesh city have collected and recorded information on 150 rural houses over 100 to 30 years (**Figure 1**). In fact, the research hypothesis is based on the fact that it is possible to use the algorithmic process with the help of supervised learning in the classification of house plans of the last one hundred years to answer the question that the classification of rural houses in Gilan What are the characteristics of form and form?

RESEARCH BACKGROUND

Typology has long been the subject of numerous studies, and in architecture, as a step in understanding and classifying the common features and principles of phenomena, research has been done. Considering that the main issue raised in the present article is the extraction of formal and form features and classification to identify species based on form and shape, the study of thematic literature indicates the lack of studies in the field. In this research, it is cognitive that the typological process has been proposed by algorithmic method for analyzing the effects and recognizing them. For this purpose, to express the research background, an attempt was made to select those researches that are most similar to the research subject as research background by researching the scientific database. Therefore, the classification of some of the studies conducted in this article are (**Table 1**).

It should be noted that according to several sources, it can be said that although various studies have been conducted in the field of typology and the results of some of these studies, including HassanPourrmarr (2014), are consistent with the

TABLE 2 | pictures of the 150 selected Talesh's rural homes, Source: Author.

case Study	The Overall Feature of floors Talesh's Plain Rural Houses
	Most of the houses are one or the most two floor. Placing the warehouse and barn on the ground floor. The arrangement of residential area above the surface of the Earth. The shape and appearance of houses in Elementary patterns have more ornamentation than the new and more perfect patterns
	Figures

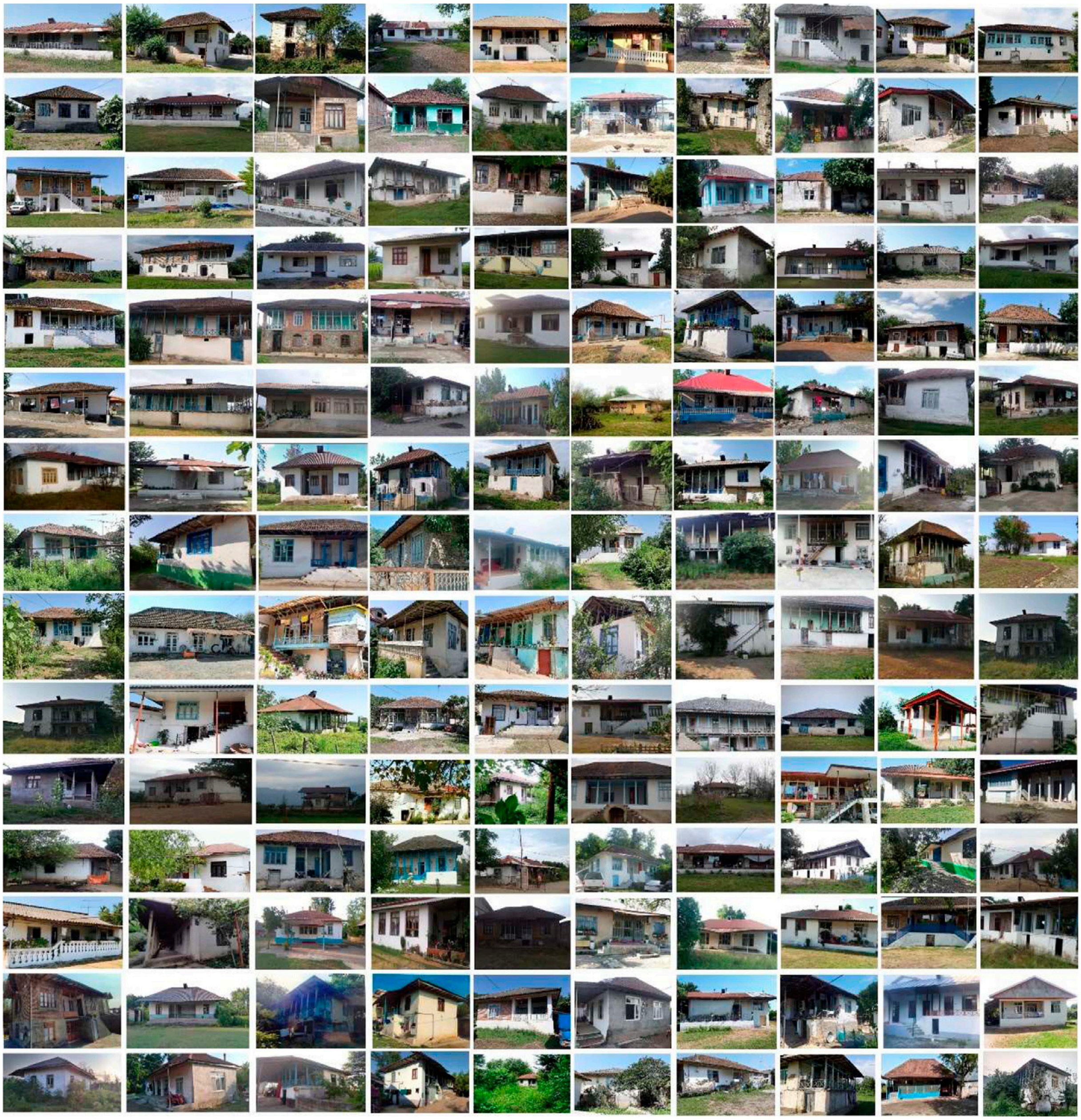


TABLE 3 | The building spaces in the village of Talesh, Source: author.

Body Building	Space Type	User	Components	Detail
open space	**court**	- The reflection of nature in the house environment	- low walls	Types of wall materials: wooden fence (Woods without the product in the form of horizontal and vertical poles)
		- Cultural and social behaviors	- garden	
		- The ventilation of the closed space	- orange trees	Chapar (the branches and leaves of the trees and The trees are greedy)
	stair	- Relationship with the first floor - connecting the courtyard with the house	Height and bottom of stair	The first - floor stairs are made of wood
Semi-open space	**entrance**	- The interface element between the outer and the inner space - spatial hierarchy	- Door	- Having a wooden door
		- Privacy control	- porch	- having a niche and a decorative pillar
	porch	- connecting the courtyard to the hall or the rooms	- Roof	- Having the entry doors into the rooms
		- specific orientation for seasonal residence - doing routine work and resting place	- Floor	- Having niche and decorative columns
		- relation to nature - natural ventilation	- wall	- Having stairs to enter upper classes
	Telar(second floor proch)	- The direction of dividing space	- Floor	- It was mostly on the southern front of the building
		- Access to the bedroom area	- Roof	- The hold of a warehouse or a barn below it
		- To use space in summer	- Column	- The rest of the summer - Possible to hold food in the winter
Closed space	**Types of rooms**	- Sleep	- Window and door	Having flexible rooms (a different user with respect to situation)
		- Living room	- Wooden ceiling	
		- cooking	- Fire box and oven	
	Barn and storeroom	- The storage area of agricultural equipment - Location of the trap	- door	- The hold of a warehouse in one of the southern corners of the building
		- storing grain	- niche	- A shelf in the wall to put things on

results of this study. Still, the survey in rural housing, using the algorithmic approach and data mining, which is in the process of rural housing design and preservation of past values, has been less studied. In the algorithmic method, by receiving unlimited data, different ideas can be easily examined simultaneously. Therefore, using this method in typology can create a proper relationship between input and output data and identify the influential factors. The accurate documentation of architectural patterns has more accurate estimation and helps achieve species recognition in less time.

Objective of the Research

The reflection of any society's cultural, social, and religious roots is reflected in its architectural body. One of the essential features of rural architecture is to pay attention to the design by the natural needs of the people and the environment and their daily activities, such as the type of living spaces of the people. Architectural examples of the coexistence of living and living spaces in this type of housing are the depth of attention to people's lives and needs, which has harmonized the physical space with the story of people's lives. Such a view of life and attention to needs and harmony with the natural environment have led to various forms of housing. Accordingly, rural house architecture has many different data that must be categorized to extract relevant data.

Therefore, this study aims to classify the architecture of rural houses in the study area based on form and shape. It also proposes a new method for categorizing rural house plans based on an analogy between plan forms. The architecture of rural houses is based on the habits, needs, and desires of the people and has a lot of different data. Moreover, the house's dimensions, size, and shape are some of the principles formed from the people's desires over time. Also, with the data mining method, it is possible to simultaneously compare a more significant number of plans with the numerical data of architectural plans. The knowledge between them, a model of evolution in dimensions and dimensions, can be compared extracted. This pattern will show the evolution of the

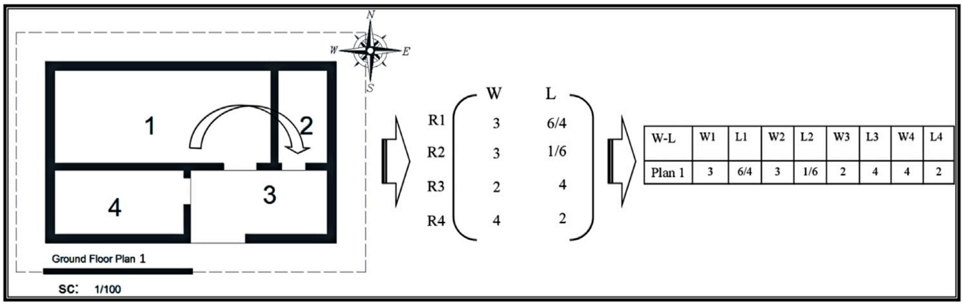


FIGURE 4 | Converting captured planes to two-dimensional vector in a clockwise direction (Rodrigues et al., 2017).

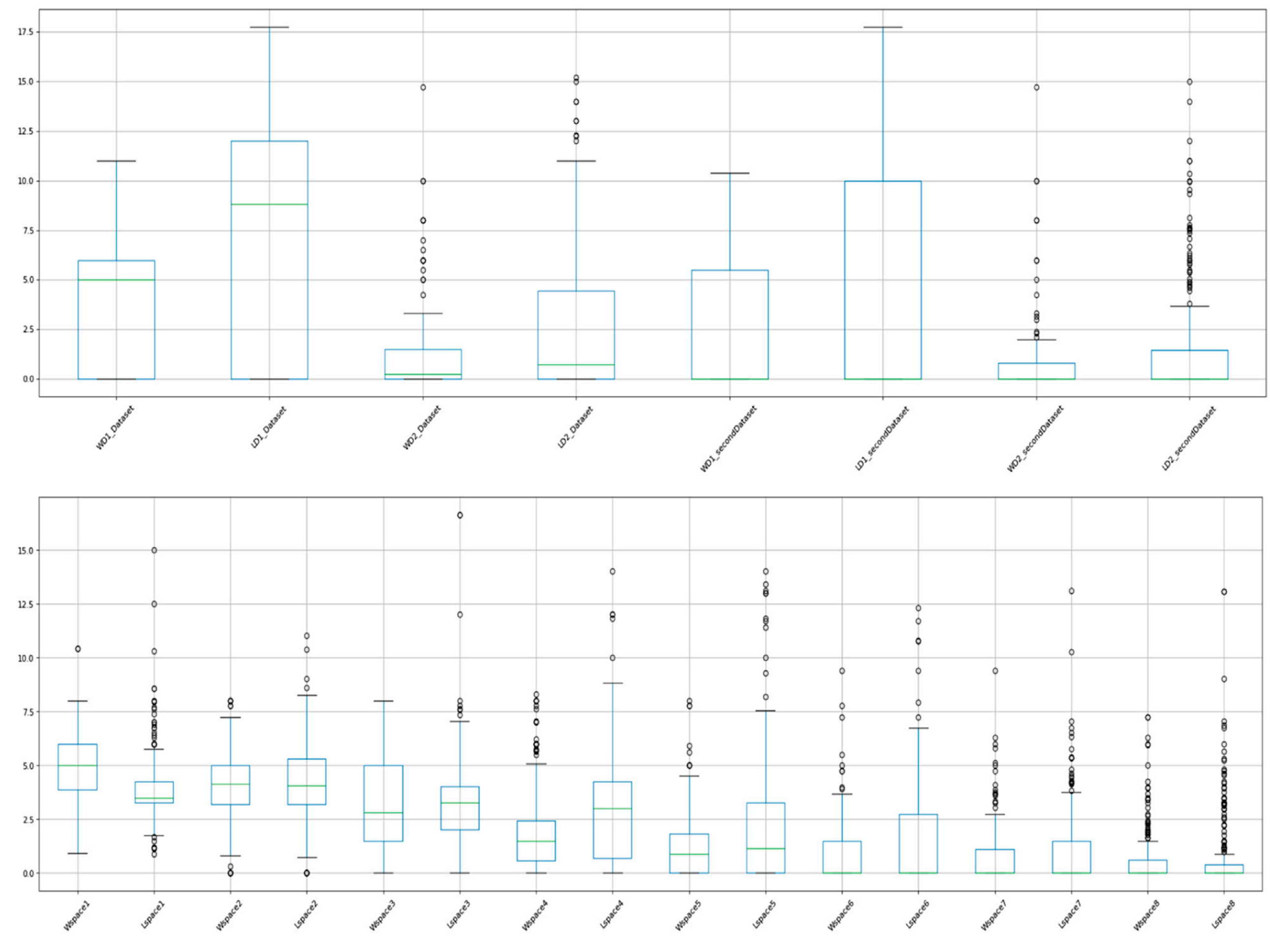


FIGURE 5 | Review of the data structure of plans (Boxplot), Source: Author.

dimensions of common and non-common spaces, which can be compared to their evolution to reach an evolved form pattern. Therefore, in addition to the new needs of residents, inspire local architects and designers in designing rural homes (Verma and Thankur, 2010; Su and Yan, 2015; Torkashvand and Raheb, 2015).

RESEARCH METHOD

Rural housing, at least in its physical form, is the result of the interaction between human needs, including livelihood, cultural and biological, with the surrounding environment. Depending on the characteristics of the environment and human needs and

FIGURE 6 | Sample structure of plans studied in three-dimensional space, Source: Author.

capabilities, this relationship has a different quality. It, therefore, will be the source of the emergence of "different forms of housing." Accordingly, the approach of the present study is to introduce the form of houses that are the product of a relationship that is established between human needs and the environment. Studying the formal features obtained, which are the product of these factors, and applying them in today's world can be used in home improvement and renovation. Therefore, in this approach, the body of the building has been the focal point. Therefore, other aspects of the building related to other fields of science, such as sociology, economics, etc., can be studied in other studies.

In the field of typology, one of the purposes is to understand the set of information that exists within a type or species of the object and to ensure its survival to the internal information that lies in its space (Hillier and Hanson, 1984). the use of algorithmic technique With the help of a computer, it can help classify and analyze it. Because internal information in typology, such as house plans, can be converted into coding, algorithms and machine learning techniques can also be used. In artificial intelligence, the machine is allowed to observe a wide range of data in a specific field to perform operations such as decision making, classification and forecasting (Ashtari et al., 2021). The basis of the research method used in this research is proportional to its nature, which is considered applied research. Typology is a precise methodological process described below (**Figure 2**).

Data Collection

Rural housing in the Gilan province of Iran, due to climatic differences, livelihood, etc... follow different patterns and do not have the same structure. In general, diverse morphology in Gilan province, including coastal areas, plains, foothills, and mountains, has provided a diverse area for forming settlements. Coastal and plain settlements have a flat topology and slight difference in them. While in the foothills, settlements have faced the slope of the land and have tried to adapt to it. Mountain settlements often include this principle and are formed along the slope to avoid colliding with the slope.

Accordingly, considering that the selected houses in the present study are located in the plains of Gilan, the architecture of these houses, like all other indigenous architectures, is based on a wise and cost-effective response

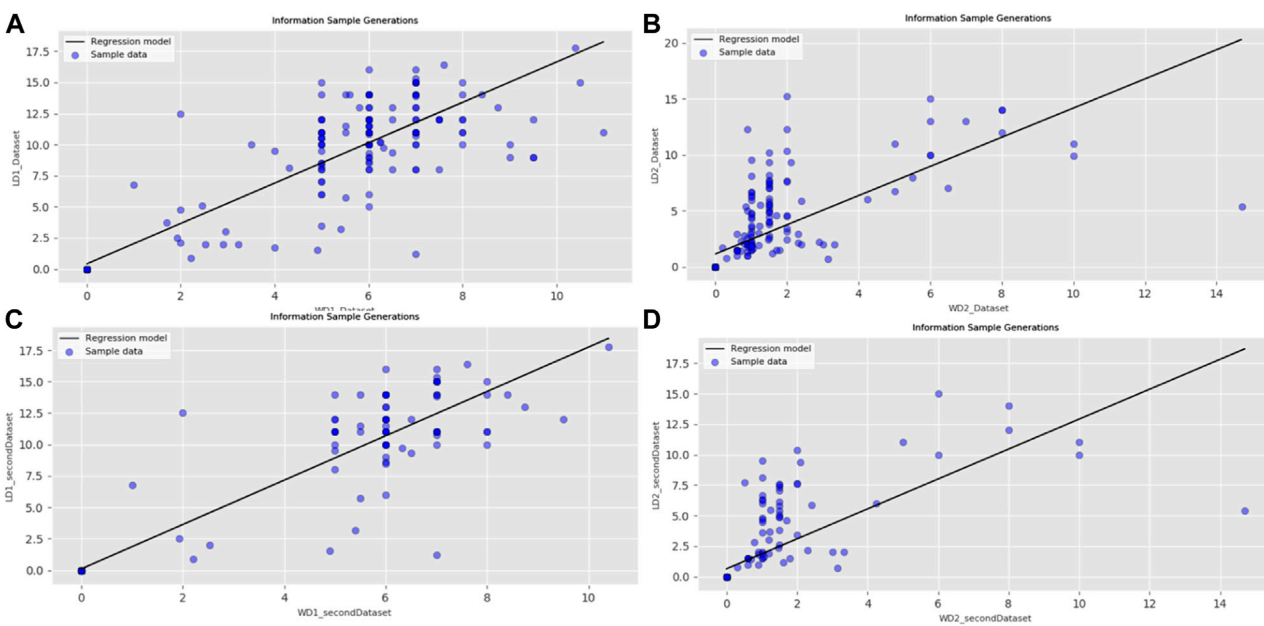
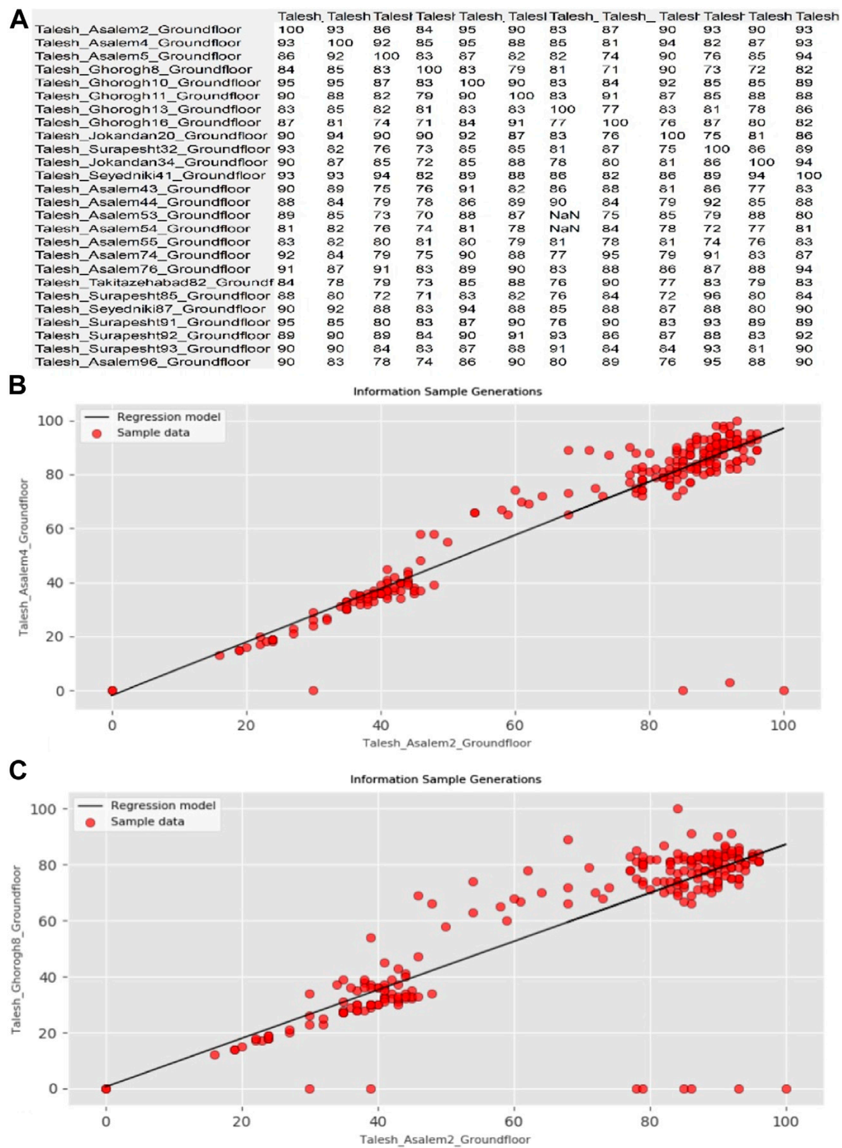


FIGURE 7 | Examination of plan data frequency, Source: Author: **(A)** 1 Frequency of ground floor plan data house number, **(B)** 2 Frequency of ground floor plan data house number, **(C)** 1 Frequency of first floor plan data house number, **(D)** 2 Frequency of first floor plan data house number.



A	Talesh	Talesh	Talest	Talest	Talesh	Talesl	Talesh_	Talesh_	Talest	Talest	Talesh	Talesh
Talesh_Asalem2_Groundfloor	100	93	86	84	95	90	83	87	90	93	90	93
Talesh_Asalem4_Groundfloor	93	100	92	85	95	88	85	81	94	82	87	93
Talesh_Asalem5_Groundfloor	86	92	100	83	87	82	82	74	90	76	85	94
Talesh_Ghorogh8_Groundfloor	84	85	83	100	83	79	81	71	90	73	72	82
Talesh_Ghorogh10_Groundfloor	95	95	87	83	100	90	83	84	92	85	85	89
Talesh_Ghorogh11_Groundfloor	90	88	82	79	90	100	83	91	87	85	88	88
Talesh_Ghorogh13_Groundfloor	83	85	82	81	83	83	100	77	83	81	78	86
Talesh_Ghorogh16_Groundfloor	87	81	74	71	84	91	77	100	76	87	80	82
Talesh_Jokandan20_Groundfloor	90	94	90	90	92	87	83	76	100	75	81	86
Talesh_Surapesht32_Groundfloor	93	82	76	73	85	85	81	87	75	100	86	89
Talesh_Jokandan34_Groundfloor	90	87	85	72	85	88	78	80	81	86	100	94
Talesh_Seyedniki41_Groundfloor	93	93	94	82	89	88	86	82	86	89	94	100
Talesh_Asalem43_Groundfloor	90	89	75	76	91	82	86	88	81	86	77	83
Talesh_Asalem44_Groundfloor	88	84	79	78	86	89	90	84	79	92	85	88
Talesh_Asalem53_Groundfloor	89	85	73	70	88	87	NaN	75	85	79	88	80
Talesh_Asalem54_Groundfloor	81	82	76	74	81	78	NaN	84	78	72	77	81
Talesh_Asalem55_Groundfloor	83	82	80	81	80	79	81	78	81	74	76	83
Talesh_Asalem74_Groundfloor	92	84	79	75	90	88	77	95	79	91	83	87
Talesh_Asalem76_Groundfloor	91	87	91	83	89	90	83	88	86	87	88	94
Talesh_Takitazehabad82_Groundf	84	78	79	73	85	88	76	90	77	83	79	83
Talesh_Surapesht85_Groundfloor	88	80	72	71	83	82	76	84	72	96	80	84
Talesh_Seyedniki87_Groundfloor	90	92	88	83	94	88	85	88	87	88	80	90
Talesh_Surapesht91_Groundfloor	95	85	80	83	87	90	76	90	83	93	89	89
Talesh_Surapesht92_Groundfloor	89	90	89	84	90	91	93	86	87	88	83	92
Talesh_Surapesht93_Groundfloor	90	90	84	83	87	88	91	84	84	93	81	90
Talesh_Asalem96_Groundfloor	90	83	78	74	86	90	80	89	76	95	88	90

FIGURE 8 | (A) Part of the percentage similarity matrix of plans **(B,C)** Illustrating the percentage of similarity of 48 plans with each other Source: Author.

TABLE 4 | Minimum and maximum spatial dimensions consisting of 48 frequent patterns, Source: Author.

Space	Min	Max	Space	Min	Max	Space	Min	Max
Width of the ground floor	5.00	8.00	room width	2.50	6.00	Kitchen and dining room width	1.75	6.50
Length of the ground floor	3.50	12.00	room length	2.50	6.25	Kitchen and dining room length	2.00	8.00
Width of the first floor	5.00	7.50	Kitchen width	1.80	5.50	Living room width	3.50	5.50
Length of the first floor	3.00	12.00	Kitchen length	1.40	4.35	Living room length	3.75	7.50
Drawing and living room width	2.60	6.50	Porch width	1.00	4.76	Barn width	4.50	5.50
Drawing and living room length	3.00	7.50	Porch length	1.55	11.60	Barn length	2.50	5.44
Bedroom and living room width	2.55	5.50	Warehouse width	1.30	6.55	Vestibule width	1.18	2.25
Bedroom and living room length	3.00	7.46	Warehouse length	2.70	5.48	Vestibule length	1.90	7.25
Washroom width	1.52	2.55	Washroom length	1.35	2.50	Stairway width	0.70	2.00
						Stairway length	0.30	5.33

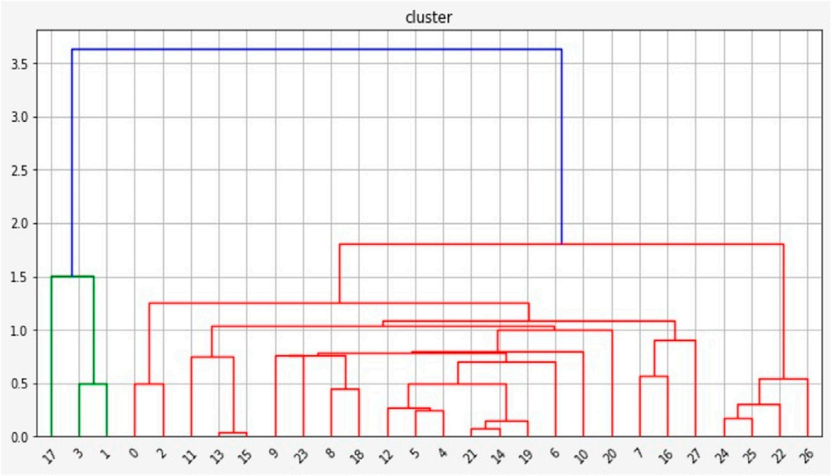


FIGURE 9 | Classification of 48 repetitive plans in the form of tree diagrams, Source: Author.

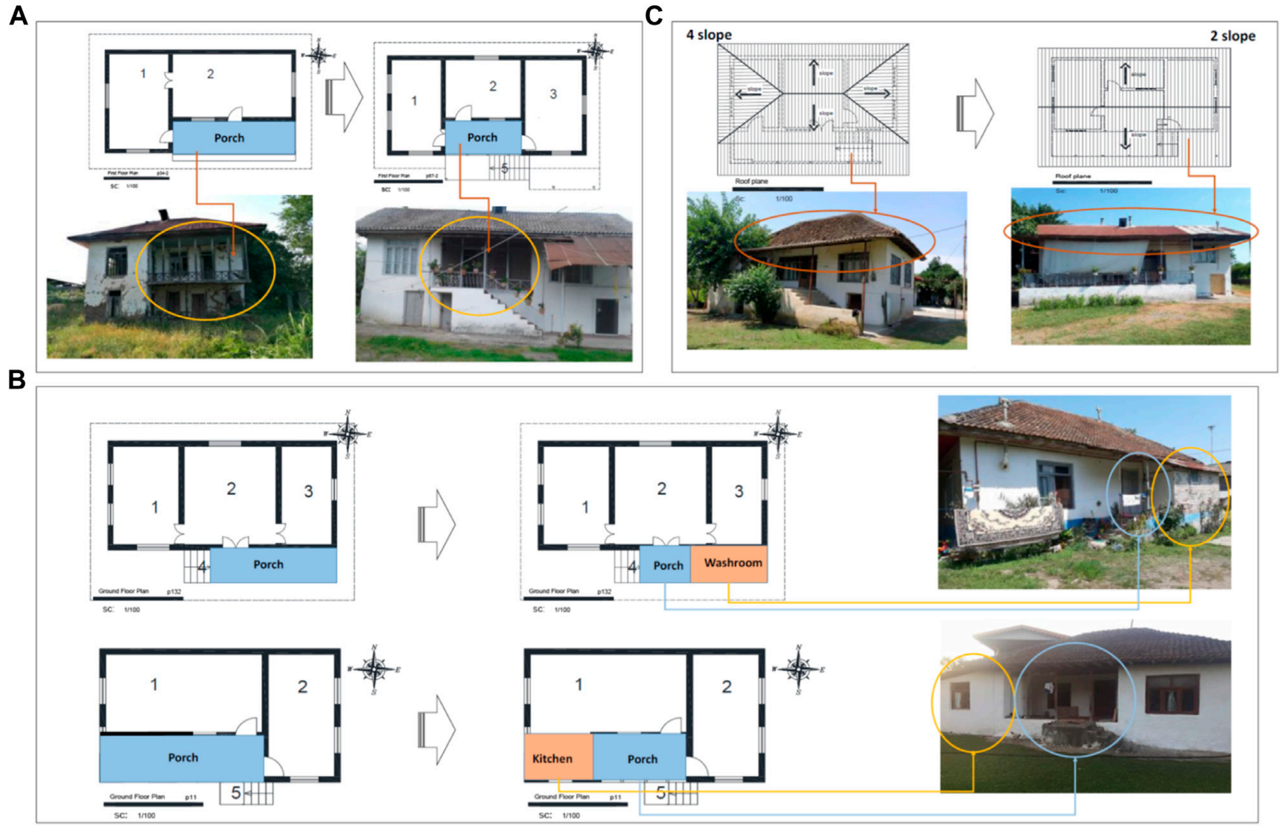


FIGURE 10 | Changes made to the form of houses **(A)** Moving the porch to the central part **(B)**Transfer of service space to the porch and **(C)** Deformation of the ceilings in the contemporary era, Source: Authors.

to human social relations, difficult temperate and humid climate conditions., Executive capabilities and available materials have been formed. However, what distinguishes the architecture of this area is the combination of its formal elements. Therefore, in selecting samples, houses that have historical value and are affected by the climate and living conditions of the people and the minor changes that have been formed in them were selected. Because for sorting, it is necessary to extract features that have been added and reduced in the house over time.

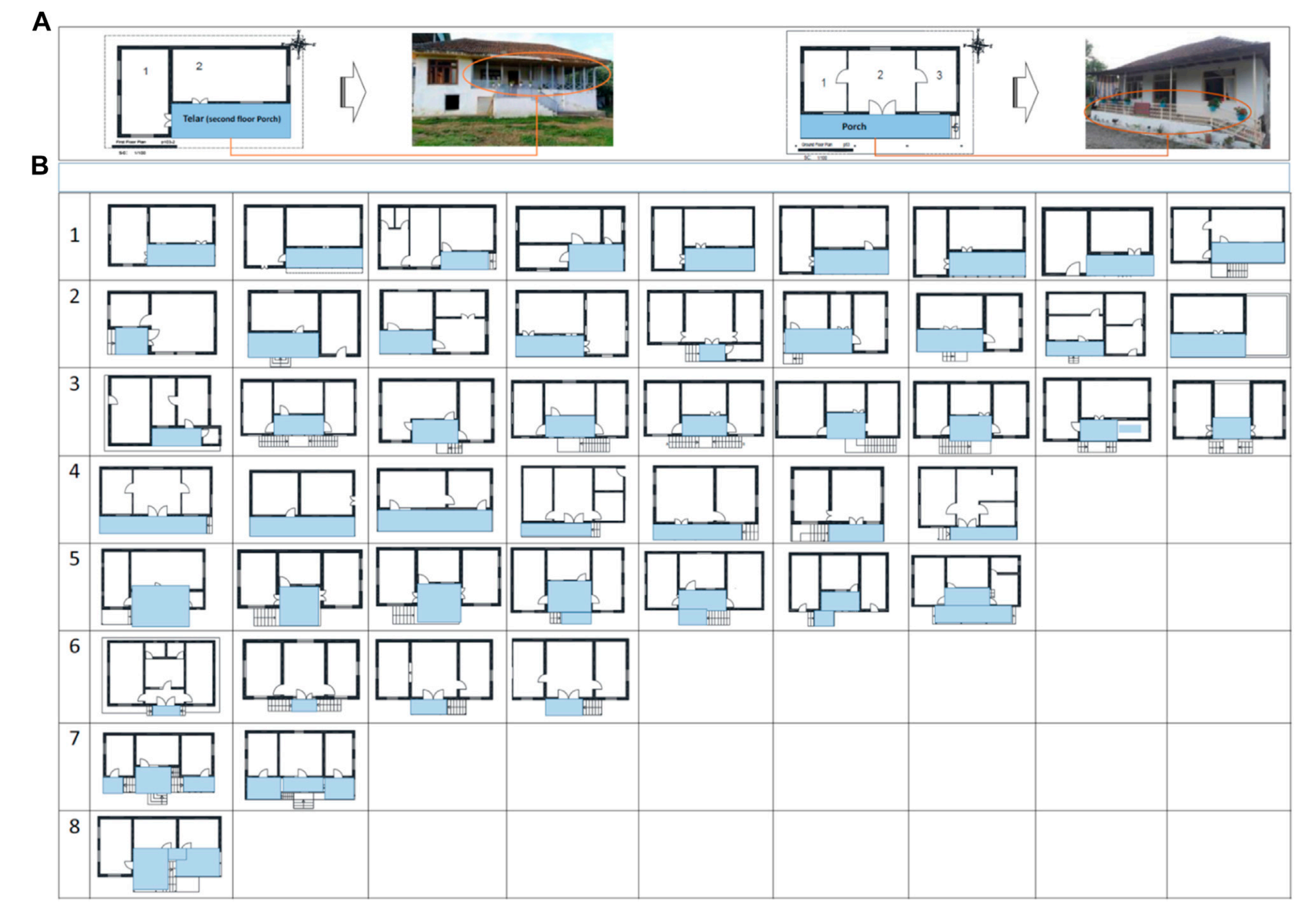


FIGURE 11 | Classification of houses **(A)** An example of a single-story house and Tellar house **(B)** Classification of form and location of porches, Source: Authors.

In general, in collecting research information and data, according to the purpose of the research, which is the formal classification of rural houses in this area, in recognizing the formal patterns of indigenous rural housing architecture from the field method (drawing house plans and also obtaining comments). Residents used by navigation). In collecting documentary studies, following the subject of research, the results and analyses of previous projects have been used to avoid duplication and supplement previous studies using the library method. In the field studies that follow the documentary studies, among 10 villages in Talesh city, 150 rural houses with a historical and valuable texture in a plain area dating back 30–100 years have been studied. The selection of rural houses is one of the essential measures in the field studies stage. It has taken up a large part of the research time because the lack of visual information and recorded statistics of native houses in this area caused the plan of 150 rural houses to be used in research by the researcher Rolveh and drawn in AutoCAD software**.**

Data Analysis

In quantitative data analysis of the research, plan analogy has been used using the cosine distance method, which is obtained through a mathematical relation and coding in *Python* space. Architectural plans are critical architectural information with a vast and vital information load that cannot be evaluated without changes and converted into numerical vectors. Therefore, after collecting the data through the drawn plans and transferring them in the form of a matrix, all the data for comprehensibility, logical classification and at the same time fast processing, with the help of mathematical language, normalization and Converted to codes 0 and 1. These data are also measured by the cosine similarity formula, a measure of similarity and the basis for calculating the angular cosine distance between two vectors. Therefore, if two vectors are compatible (in this criterion, it is a sign of complete similarity) that the angle between the two vectors is zero, its value will be equal to 1. In the most minor similarity of the two vectors, i.e., if the angle between the two vectors is 180°, the result of this criterion will be -1 (**Figure 3**).

Therefore, by visualizing the data by *Python* and analyzing similar plans, classification will be done, which is discussed in the continuation of the research.

Statistical Community Selection

Typology is meaningless without site selection. The selected bed is the plain part of Talesh city in Gilan province in the present study. They occupy one-third of the province's lands and most of the province's population lives in these areas (Khakpour, 2005, 64).

The climate in the plains, which stretches from the foot of the mountain to the shores of the Caspian Sea, is relatively temperate. Due to its proximity to the Caspian Sea and the short distance between the mountains and the sea, these areas have a moderate temperature with a limited thermal range. Hot and humid summers are the main features of this type of weather. In these areas, due to large flat areas, uninhabited settlements have been formed. In this area, in the areas where water resources are found, settlements are formed in connection with it. Therefore, due to the hot weather and the presence of high humidity, the shape of houses is often broad and has wide openings, and due to the intensity of rain, sloping roofs are visible. Due to the favorable natural conditions in this region, the density of settlements is higher. They have the possibility of more growth and development; For example, villages with more than 200 households can be seen in these areas (Al-Hesabi and Raheb, 2009, 197).

Talesh rural housing in the past, with its different appearance, is a simple adaptation of the nature and geography of the region and meets the needs of people whose economic activities and biological culture are different from other parts of Iran. The architecture of Talesh rural houses, which has unique features in terms of structure and form, but due to factors such as technology, migration, etc., have undergone many changes over time that these changes in the course of life Its inhabitants have made a significant impact. Therefore, regardless of the positive and negative aspects of these developments, the need to introduce and recognize these houses is essential. Because the buildings and components of these rural houses, due to the execution technique, form, and use of appropriate materials, ... can be reused in today's designs. Also, due to the lack of written information about the valuable architecture of this area, it has been possible for the researcher to have a deep knowledge of the area.

Therefore, according to the selected area in the present study, the most important causes of selected rural houses can be listed as follows:

1) Houses that were less changed over time
2) The scattering in the geographical location of Talesh
3) The variety of the plan features, the spatial relationships
4) The dominant materials, the variety and coverage of the roof
5) the size of the house, the number of floors
6) worthy local homes in the region for the period between 100 and 30 years.

It is also worth mentioning that due to the size of the area and the large number of villages located in Talesh city, it has not been possible to navigate the entire area. To limit the study context, according to the studies conducted, the villages with the most samples of traditional houses were selected and fewer studies were conducted in them. **Table 2** shows the categories of selected samples.

General Knowledge of Indigenous Housing in the Talesh Region

The physical structure of traditional houses indicates their clever design in man's interests and the environment. The builders of these indigenous units have tried at all times and places to create a friendly relationship between the environment, culture and form. Architecture directs living spaces in the direction of humanization (Basiago, 1999, 146). The creation of air blinds was scattered and around them, there were spaces in the form of fields and service elements such as stables, straw barns, and rice seedlings.

Regarding the zoning and determination of private territory and semi-public spaces of rural housing units, the hierarchy of access to housing through the passage, due to the kinship and familiarity of the people of a village with each other, does not have different degrees and is not clear. Also, the border between two residential units is contractual. There is no strong visual privacy for each house, and interference is observed in private and public areas (Khakpour, 2007, 76). The fusion of livelihood with the body has a special place in indigenous housing that distinguishes it. And related to each other through a porch (terrace) on the upper floor on the ground floor or covered Telar (Cetam) on the first floor, defines the scope of the private area.

Accordingly, in the native architecture of Talesh, considering that its physical elements were designed in an integrated manner and in harmony with the architectural structure of the building, because in the past, all components and elements of the building were formed based on the needs of users also in interaction with climatic conditions and livelihood, and the form of the constituent spaces was directly related to the type of function. For this purpose, physical elements in rural houses have been tried to meet these needs by combining three patterns of open space, closed and semi-open, which is shown in the following table (**Table 3**).

ANALYSIS OF FINDINGS

Sorting Houses in Terms of Dimensions and Size

In the present study, considering that the dimensions of spaces are regarded as one of the effective indicators in the classification of plans, analyzing the data from box diagrams is a standard method for displaying data distribution in *Python*. To draw this diagram, the plans in the database are processed in a clockwise direction and the length and width of the spaces are converted into two-dimensional matrices (**Figure 4**).

Finally, the numbers processed by the *Python* programming language libraries show the data classification of 150 rural houses in the Gilan Plain, which have plans with different dimensions and shapes in squares. The middle rectangle in this box diagram shows the frequency of the data and the initial and final squares of the lowest and highest numerical values, respectively. The points on the box diagram (**Figure 5**).

Accordingly, according to the diagram shown, in which the length and width of the spaces that make up rural houses are written in its horizontal axis and its vertical axis is the dimensional range of these spaces in terms of meters, the plan of 150 rural houses studied has dimensions in general. It is common with a width between 0–11 m and 0–18 m. The repetitions in terms of dimensions and size were selected based on the middle rectangle.

Also, based on **Figure 6**, different types of architectural plans can be observed, in which each of the color circles represents a plan of 150 plain houses, which are studied in this study. The 3D space is illustrated using the *Python* programming language. The primary color spectrum represents the main categories of plans and the mixed colors represent the plans in the middle dimensions. Therefore, there are four general categories in terms of dimensions and size of the plans, which are displayed with the main colors of yellow, green, red, and blue. The plans did not have a specific standard in terms of dimensions and size, and because they were made according to the needs of the people, they had very different structures and divisions.

Typology of Repetitive Patterns

In the research, according to **Figure 7**, the regression method in which the constituent data is taken from the plan of 150 houses is used to obtain the length and width of repetitive patterns that are actually the most abundant in terms of dimensions and size.

Therefore, according to the diagrams illustrated by *Python*, the two diagrams a and b, which are related to the ground floor plans, and the c, d diagrams, which are related to the plans with the first floor, show their vertical and horizontal axes, respectively. It gives the length and width of the sample of the studied plans and constituent spaces, which are indicated by the abbreviation LD, WD. The direction of the line indicates a positive correlation between the movement of plans and the space of harvested plans. Considering their age, about 30–100 years, they have increased in frequency and dimensions over time and from the least space to most of the space is inclined. Also, in these diagrams, the presence of colored circles indicates the pattern of 150 cells studied, and the bolder and overlapping pigments indicate the abundance of redundant data and patterns in that range. For this purpose, according to plans selected with the help of Boxplot and the studies performed in the abundance of its data, the plan of 48 rural plains is one of the most frequent patterns. According to the vector-matrix, their width is 5–7 m and their length is 8–15 m.

Similarities of Plans

After reviewing and selecting repetitive patterns, the coding process will be coded on the selected plans. Therefore, by choosing the 48 plans with a repetitive pattern, each plan is compared with 47 others by spatial dimensions and percentage similarity. "Figure" is written. In **Figure 8A** similarity of the plans, less than 70% similar to each other, is marked separately with the letter NaN.

The study of the percentage similarity matrix of the planes illustrated by *Python* was used to obtain repetitive patterns with a similarity of over 70%. According to **Figures 8B,C**, the comparison of the similarity of planes with each other is illustrated by linear regression. The horizontal and vertical axes represent the number 0–100% similarity. The higher the circles on the line, the higher the similarity of planes and the lower the percentage of similarity (**Figures 8B,C**). This study shows that among the 48 repetitive patterns, 80% of the plans were more than 70% similar to each other.

Finally, as shown in **Table 4**, according to the minimum and maximum dimensions of the spaces that make up the 48 common patterns obtained from the study of the dimensions of the spaces that make up the rural houses of the Gilan plains, the plans are categorized as The tree diagram is illustrated with the *Python* programming language.

Plans No. 24, 25, 22 and 26 are in the same category because of their high similarity in their structure, and other plans are also classified in this way (**Figure 9**). The similarity percentage is obtained from the similarity of the dimensions and size of each plan's spaces in its structure. It consists of two main categories and 8 sub-categories. The main category plans in the studied plain houses include single-story and Telar plans. Based on the spatial dimensions of the repetitive plans, the hall houses have dimensions with a length of 3–12 m and a width of 5–7.50 m. Its single-story houses are in the dimension range of 5–8 with a width of 3.50–12 m.

Also, by examining the percentage similarity of the plan of the main categories according to the extracted matrix (**Figure 8**). it can be stated that single-story houses have more than 70% similarity with each other except for repetitive patterns, Is in this area.

CONCLUSION

Considering that each geographical region has its climate, culture, etc., which differentiates that region from other regions, housing construction in each region also needs its pattern. For this reason, modeling from other regions has increased the consumption of non-renewable energy, which in addition to economic aspects, increases environmental pollution. Adaptation of housing to environmental conditions also brings comfort to residents. Therefore, the necessity of using local architectural methods and physical elements of these houses can be considered according to the region's climate in the rural context today. Therefore, after examining the form of the plans, what was extracted in this study is the existence of over 75% similarity in the repetitive plans, which indicates a similar course in the design of the rural houses of Talesh.

In the present study, the study results of 150 rural houses in Talesh have been studied based on the percentage of similarity of dimensions and size of plans and comparative observation of patterns. The results show that houses are often affected by climatic characteristics and types of livelihood activities of local people. These houses have an axial and linear form with a rectangular plan and, in most cases, are rectangular in shape and have a length of 5–7.5 and a width of 3–12.5. In these houses, porches and sloping roofs have played an influential role in forming their form. Moreover, the houses were usually directly connected to their external space, such as a passage by creating a continuous columnar porch around their space. The passage and its interior spaces were also related to the external space. They were designed and built. The porch space, a semi-open space in the southern part, has been moved to the middle of most buildings in the contemporary era and provides access to the rooms only for a corridor (**Figure 10A**).

In some cases, as shown in **Figure 10B**, part of the service space, such as toilets, has been moved from the yard to the porch space and its length has been reduced.

In this building, where the roofs are sloping (mostly 4 slopes) and its protrusion is the size of a porch to prevent rainfall from colliding with the body of the building, in the contemporary era, more use of Aleppo and deformation in the form of 2 slopes Is given (**Figure 10C**).

Also, by examining 48 repetitive plans with a high percentage of similarity, it shows that Gilan plain houses are generally composed of two categories of common patterns. The main categories are single-story houses and Telar houses (porches upstairs). According to the similarity performed, high-rise houses in these areas are the most frequent patterns (**Figure 11A**).

It should be noted that considering that the porch is the central core of the architecture of houses in this area, by reviewing 48 repetitive plans, the main category houses according to the shape and location of the porch, are also composed of 8 sub-categories, which in **Figure 11B** Shown. It should be noted that on the ground floor of the building, in two-story houses, it has been used more as a warehouse and storage place for food, and in some cases as a kitchen, which in recent times has become more of a residence. Also, in Telar houses, the direction of the ground floor rooms is not in the same direction as the upper floor rooms, and the number of spaces on the ground floor is more than the upper floor. Windows in these areas, which have provided natural ventilation to the building on all four sides of the building many times a year, are fewer on the ground floor than on the upper floor (Bazen and Bromberje, 1986; Bromberjeh, 1991; Elsayed et al., 2014; Mazandzani and Reza, 2009; Kasmaei, 2006; Al Qady and Kandil, 2014; Apoorva et al., 2018; Rodrigues et al., 2013; Rodrigues et al., 2014; Su and Yan, 2015; Torkashvand and Raheb, 2015; Verma and Thankur, 2010).

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

SG: Literature review, data collection, paper draft, Visualization MY: Methodology, final editing, Validation MB: data primery analysis.

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BIM-based model for sustainable built environment in Saudi Arabia

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BIM has had a significant influence on the building and construction industry, contributing to efficiency, productivity, and cost-effectiveness improvements. BIM technology's integrative nature makes it a perfect platform for adopting sustainable techniques in new construction, renovation, and retrofitting of existing structures. Saudi Arabia's market gasoline prices fell drastically between 2018 and 2020, forcing the Kingdom to create its 2030 vision. The 2030 vision seeks to transform the Kingdom of Saudi Arabia (KSA) into an ideal sustainable society by lowering its dependency on oil and constructing more sustainable buildings and infrastructures. The number of green buildings and high-performance buildings in the KSA is inadequate, and the rate of change is too slow. Due to KSA's need to enhance its built environment, it established a new green building rating named "Mostadam." Currently, there is no metric to measure the roadmap to achieve the aspects of the KSA's 2030 vision, and the number of green buildings in the KSA is very low compared to other countries. Therefore, there is an urgent need to translate the KSA's green objectives into effective regulations. To attain this goal, there must be uniformity across jurisdictions in order to make sound and well-informed decisions about adopting and enforcing sustainability. This research intends to focus on the advanced capability of using BIM and creating a BIM-Based model to help facilitate the green building certification in Saudi Arabia that supports its vision of 2030. The research proposes a new strategy based on the integration of BIM and Mostadam green building rating systems where a BIM plug-in can aid in achieving the 2030 envisioned water sustainability goal and implement sustainable design principles in Saudi Arabia. Autodesk Revit and Dynamo were used for programming and visualizing the model. The model focused on one main category of Mostadam's Green Building Rating System: water conservation. This study used a mixed methodology that combines qualitative and quantitative approaches. Phase I of this study focuses on the literature review and collection of available data about BIM, Green Building Rating Systems, and the KSA 2030 vision. Phase II aims at collecting data from an online survey sent to AEC professionals. Moreover, phase II of this study includes developing a BIM-Based model using Autodesk Revit and Dynamo. Phase III embraces the validation of the model using a prototype and a case study. Driven from the data collected, the new BIM-Based model assisted in achieving the KSA 2030 vision by reducing the water consumption when compared to the baseline water consumption. The model's constraints are presented along with future phases of the study.

KEYWORDS

BIM, sustainable built environment, sustainable buildings, green building rating system, Saudi Arabia, 2030 vision

1 Introduction

Following the discovery of oil in Saudi Arabia, petroleum became a primary industry. Saudi Arabia's economy has grown and has been developing at a rapid pace since the 1980s, fueled by massive earnings from oil exports. Despite its past underdevelopment, Saudi Arabia's wealth of resources has resulted in a number of development initiatives that have modernized the country and contributed to a low unemployment rate (Mahmood, Alkhateeb, & Furqan, 2020). Saudi Arabia's market gasoline prices fell drastically between 2018 and 2020, forcing the Kingdom of Saudi Arabia (KSA) to establish its 2030 strategy. The 2030 vision aspires to transform Saudi Arabia into an ideal sustainable society by lowering its dependency on petroleum, building more sustainable structures, and utilizing renewable energy resources. When designing a perfect sustainable community, equal access to nourishment, healthcare, clean water, shelter, education, energy, economic opportunities, and jobs must be provided (Mostadam Green Building Rating System, 2020).

The KSA is the world's leading producer and exporter of petroleum liquids and is also considered the Middle East's leading consumer of petroleum liquids (EIA, 2020). The country's economy is based on oil, and the energy sector is fully dependent on fossil fuels. In the KSA, investing in renewable energy and taking public transportation is discouraged; therefore, the Kingdom faces a severe problem with green gas emissions (Rahman & Khondaker, 2012). KSA is ranked 61st in the 2014 Climate Change Performance Ranking, the final position on the index (Burck, et al., 2013). As a result, it is critical for the KSA to reduce its environmental footprint and improve building sustainability (Taleb & Pitts, 2009).

Building Information Modeling (BIM) has been booming in the architectural, engineering, and construction (AEC) industry as it is being used in parallel with the continued momentum of the green building initiative during the past decade. Although entirely unrelated concepts at first glance, BIM and green building collectively are able to best address the unprecedented challenges in productivity and sustainability encountered by the AEC industry. Building Information Modeling has a tremendous effect on the building industry by increasing performance, cost-effectiveness, and productivity. Current building practices need more efficient tools to design high-performance, safe, and sustainable buildings that can achieve low carbon footprints (Everett et al., 2017). To do so, professionals in the building sector are increasingly expected to use environmental assessment systems to evaluate building efficiency in the design, construction, and operational phases (Singh et al., 2019).

Although various frameworks are such as BREEAM, LEED, CASBEE, and Mostadam now available to provide environmental assessments (Trusty, 2000), there is still a lack of convenient, reliable, and highly efficient tools that can be utilized to manage the overall assessment process using these schemes (Thérivel and Paridario, 2016; Kibert, 1994; Kibert, 2007; Kibert et al., 2002). This lack of tools has raised several critical issues that need to be considered while assessing the sustainability performance of buildings (Jaffe et al., 2005). Therefore, the introduction of Building Information Modeling (BIM) has presented a unique opportunity to optimize the sustainability performance of buildings (Counsell, 2016).

The goal of the 2030 vision is to reduce the KSA's reliance on petrol and make the KSA a sustainable society (Jurgenson et al., 2016). Since the number of high-performance buildings in Saudi Arabia is inadequate and the rate of change is too slow, especially with climate change and the oil shortage (Economic Indicators, 2022) and (Mosly, 2016), Saudi Arabia must change its built environment and sub-structure more rapidly, and BIM can accelerate the progress in Saudi Arabia. Currently, there is no metric to measure the roadmap to achieve the goals of the 2030 vision, and the number of green buildings in the Kingdom of Saudi Arabia is very limited. To tackle those challenges, integrating BIM and green buildings needs to be pursued. The fundamental contribution of this research will be the unique approach it proposes to fulfill green building certifications such as Mostadam by integrating the functionalities of BIM. Consequently, this study aims to formulate a BIM-Mostadam model to help facilitate the green building certification process in Saudi Arabia that will support the Kingdom's 2030 vision (Hashmi, 2016), (Mostadam Green Building Rating System, 2020) and (Mosly, 2016).

The research objectives include 1) reviewing existing methods and frameworks to measure sustainability, 2) identifying the critical elements of the KSA 2030 vision, and 3) integrating the findings into a BIM-based model for sustainability in the KSA. Due to the limited number of green buildings in Saudi Arabia, this study aims to formulate a new BIM-Based model for Sustainable Built environments in Saudi Arabia that supports the Kingdom's 2030 vision. Therefore, the primary goal of this study is to develop a BIM-Based model for sustainability in the KSA to achieve the Kingdom 2030 vision. The study asks the following question: 1) How can Autodesk Revit be utilized to assist the Mostadam certification? 2) How can BIM be utilized to integrate the objectives of the KSA 2030 vision within the Mostadam rating system?

This research follows a mixed methodology that includes both qualitative and quantitative approaches to address the research questions. Phase I of this study focuses on the literature review and collection of available data about the 2030 vision. Phase II aims at collecting data from an online survey from AEC professionals. Moreover, phase II of this study includes developing the framework for the BIM-Mostadam sustainability platform. Phase III embrace the validation of the framework using a case study. Driven from the data collected, a new BIM-Mostadam framework will assist in attaining the KSA 2030 vision.

2 Literature review

2.1 Saudi vision 2030

King Salman Bin Abdulaziz, the custodian of the two holy mosques, announced and accepted the Saudi Vision 2030 in June 2016 (Government of Saudi Arabia, 2016). The 2030 Vision attempts to wean the Kingdom's economy off its reliance on oil export income and government spending, focusing instead on the development of the private sector and human capital (Hashmi, 2016; Hashmi and Alam, 2019). It includes explicit targets, specific objectives, and commitments that must be met by the Kingdom's business, public, and non-profit sectors. Several ambitious goals of the Saudi Vision 2030 include: a) reducing the Kingdom's overall non-oil government revenue from SR 163 billion ($43.5 billion) to SR 600 ($1,599 billion) by 2020, increasing to SR one trillion ($266.5 billion) by 2030; b) increasing the private sector's contribution from 40 percent to 65 percent of GDP; and c) increasing the Kingdom's share of non-oil exports in non-oil (Almasoud, 2016).

The NTP 2020 intends to implement the Saudi Vision 2030 through four essential pillars that will make this plan a reality. These four main pillars are privatization, governance, human capital investment, and economic diversification (Almasoud, 2016). The NTP is supported by six pillars:

- Reduce reliance on oil;
- Evaluate ministry performance and prevent corruption; and
- Achieve optimum energy efficiency.
- Expand sectors such as tourism and improve Hajj and Umrah operations;
- Create more jobs for Saudi citizens; and
- Use resources to support future projects (Hashmi, 2016).

Furthermore, the vision displays an attempt to improve all elements of the Saudi people's growth and well-being and safeguard and preserve the environment and its natural resources. The vision also aims to protect the environment by enhancing the efficiency of waste management, cutting down on all forms of pollution, initiating large-scale recycling projects, rehabilitating and safeguarding beaches, natural reserves, and islands and making them accessible to everyone, promoting the optimal use of water resources by making use of renewable and treated water, and eliminating desertification (Government of Saudi Arabia, 2016). The government and local private architecture and engineering communities began collaborating to define sustainability and how it may be applied.

2.2 Oil in Saudi Arabia

Saudi Arabia is a prosperous country due to its oil resources. The country contains the world's greatest oil reserves, which have significantly impacted its economic growth since the 1930s. Large-scale production did not commence until after World War II, and it accelerated in the 1960s and 1970s, transforming the country into one of the MENA region's fastest developing countries (AIA, 2014). Saudi Arabia's revenue per barrel of oil has more than doubled from $0.22 in 1948 to $1.56 in 1973 (Mahmood, Alkhateeb, & Furqan, 2020), (Mahmood, Alkhateeb, Al-Qahtani, et al., 2020) and (Mubarak and Nawari, 1999). Following the Arab oil embargo, the price continued to rise to $10 and higher in 1974. Oil revenues continued to rise, reaching more than $30 per barrel by 1982. Oil revenue peaked in December 1979 at $121.28 per barrel and again in June 2008 at $141.32 per barrel. Between 1973 and 1980, government oil revenue increased dramatically, from $4.3 billion to $101.8 billion (Mahmood, Alkhateeb, Al-Qahtani, et al., 2020) and (Conca, 2015). The abundant money from oil earnings provided Saudi leaders with the resources to pursue massive economic changes. The oil price has frequently dropped significantly; the price of a barrel of oil regularly ranges below $60, and it is not likely to increase above $100 for an extended period of time (Conca, 2015). These swings in oil revenue have forced Saudi Arabia to diversify its economy and transition away from oil dependence toward a more sustainable future (Mahmood, Alkhateeb, & Furqan, 2020) and (Mahmood, Alkhateeb, Al-Qahtani, et al., 2020).

2.3 Challenges of sustainability in Saudi Arabia

Various difficulties confront the KSA's consideration of green buildings and the acceptance of LEED-certified buildings. The climate in Saudi Arabia is not conducive to the typical sprawl of Western suburban development, and there is a lack of public awareness, a lack of stakeholder interest, low levels of investment in sustainable buildings, a lack of financial incentives, and a lack of government regulations on sustainable buildings are just a few of the issues. Another barrier to the implementation of sustainable techniques in the country is a lack of awareness among design firms about how to produce feasible, sustainable buildings that include Saudi Arabian culture in the design forms (Karam, 2010; Mosly, 2016).

2.4 Mostadam, the Saudi Arabian green building rating system

Saudi Arabia developed a new green building rating system called Mostadam in January 2020 with aid from the country's Ministry of Housing and the sustainable cleantech consultancy firm Alpin (Balabel & Alwetaishi, 2021) and (Mostadam Green Building Rating System, 2020). Their services extend from building quality assurance to sustainability evaluation.

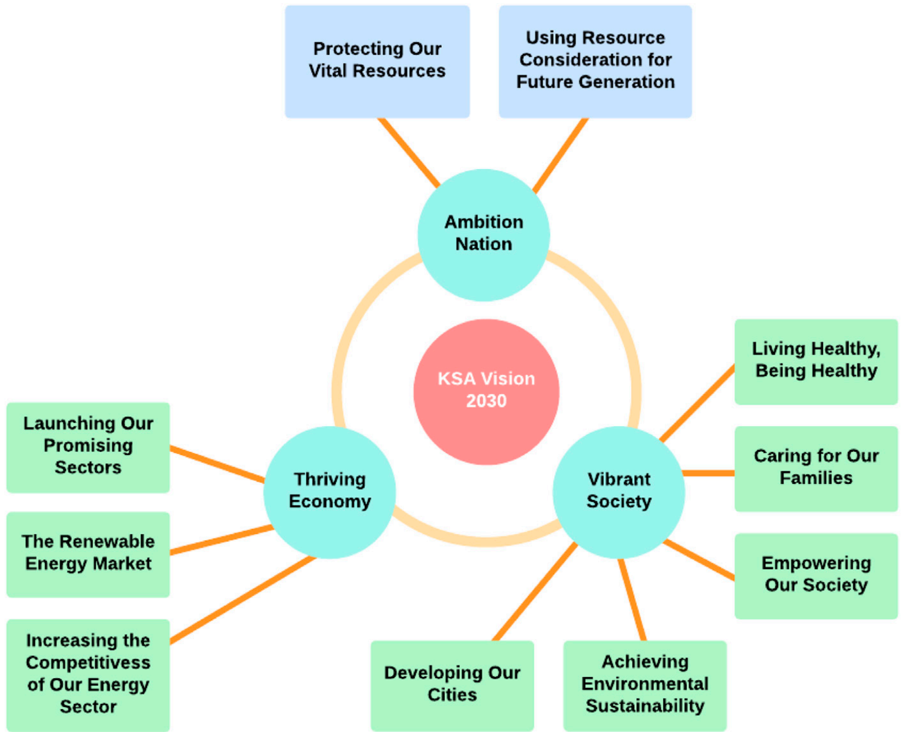

FIGURE 1
Vision 2030 and Mostadam (Modified from Mostadam Green Building Rating System, 2020).

Furthermore, the Saudi Vision 2030 objectives were inspired by this rating system (Alkahtani & Nordin, 2020). Mostadam is established to suit Saud Arabia's environmental characteristics and local climate and promotes Saudi employment and economy. In addition to that, it supports and complies with existing legislation where it aligns with the Saudi Green Building Code (SGBC) and the Kingdom of Saudi Arabia Vision 2030 (Alkahtani & Nordin, 2020) and (Balabel & Alwetaishi, 2021). Figure 1 delineates Mostadam in relation the Vision 2030. The 2030 vision focuses on three major areas that are crucial to Mostadam as a rating system:

- Water
- Energy
- Human Health and Comfort

Like other green building rating systems, Mostadam contributes to energy conservation, promotes sustainable energy usage, increases water effectiveness and recycled water use, and raises global sustainability awareness. Figures 2, 3 show Mostadam rating systems and credits (Mostadam Green Building Rating System, 2020).

An increasing number of companies and businesses are beginning to view sustainability as an instrument for profitability improvement. The adoption of UN Sustainable Development Goals is expected to provide at least $12 billion in annual business opportunities by 2030. To achieve this, companies are using frameworks such as Mostadam. The fundamental objective of Mostadam is to encourage water and energy conservation, enhance waste management, and lessen the negative impact of building operations on the surrounding environment (Alkahtani & Nordin, 2020) and (Mostadam Green Building Rating System, 2020).

As highlighted in Figure 1. The Vision 2030 prioritizes three areas—an Ambitious Nation, a Vibrant Society, and Thriving Economy. These priority areas focus on several benefits:

- Protecting vital resources.
- Using resources with consideration for future generations.
- Healthy living.
- An empowering society.
- Achieving environmental sustainability.
- Developing cities.
- Increasing the energy sector's competitiveness.
- Improving the renewable energy market (Mostadam Green Building Rating System, 2020).

The Mostadam Rating System consists of three main categories, which are: Mostadam for Residential Buildings,

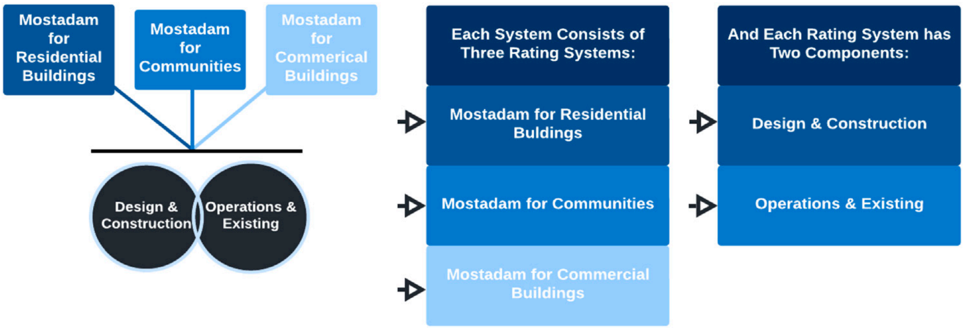

FIGURE 2
Mostadam rating systems (Modified from Mostadam Green Building Rating System, 2020).

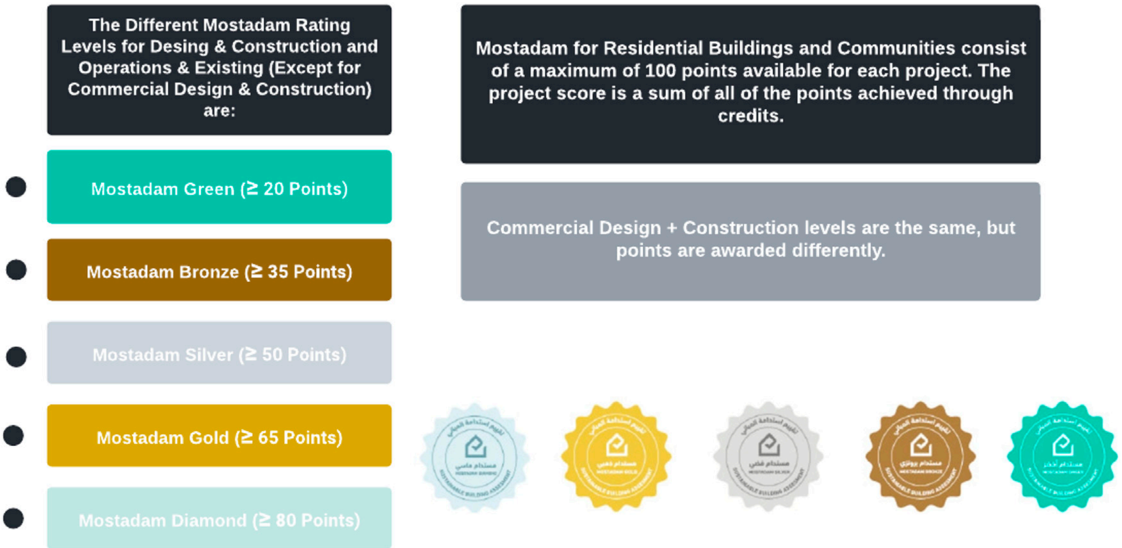

FIGURE 3
Mostadam credits (Modified from Mostadam Green Building Rating System, 2020).

Mostadam for communities, and Mostadam for Commercial buildings. Each one of these categories has two subsections (Design and Construction) and (Operations and Existing), as illustrated in Figure 2 (Mostadam Green Building Rating System, 2020).

Credits for Mostadam are illustrated in Figure 3. Mostadam credits for Residential Buildings and Communities consist of a maximum of 100 points available for each project. The project score is a sum of all of the points achieved through credits. Mostadam credits for Commercial Design + Construction levels are the same, but points are awarded differently (Mostadam Green Building Rating System, 2020).

2.5 Building information modelling

For green certification and sustainability, BIM is rich in information that stakeholders may use at various stages of the project (Autodesk 2005, 2009; Azhar et al., 2011, 2016; Mahdavinejad and Refalian, 2011; Siddiqui et al., 2019a, 2019b; Roostaie and Nawari 2022). According to Miller et al. (2015); Miller and Buys (2017), BIM is also utilized to improve the built environment's sustainability. Different sustainable design solutions can be implemented and easily traced in the BIM model. Furthermore, advanced visualization methods such as 3D renderings, green building construction animations, and solar studies can be carried out utilizing a BIM model (Azhar et al., 2017), (5 Ways Revit Supports Green Building, 2017) and (Olanrewaju et al., 2022).

Additionally, BIM's "computation and analysis ability of the model to quantify savings and benefits" goes far beyond simply enhancing visuals. It allows designers to gain new insights into their projects, reduce risk and save money through methods like 4D and 5D analysis and clash detection, as well as simplify the process of prefabrication and system coordination. With these advantages in mind, project members can create holistic system evaluations, address transdisciplinary problems, remove waste, and save costs. BIM is more than just a graphical tool; it is also a cohesive information modeling tool with the potential to favorably impact and influence sustainability, life cycle assessment, construction waste, rainwater harvesting, and energy efficiency (Langar, 2013), (5 Ways Revit Supports Green Building, 2017) and (Olanrewaju et al., 2022).

2.6 Building information modeling and LEED

Over the last decade, the rapid advance of building information modeling (BIM) technology has dramatically changed the traditional paper-based practice of the architecture, engineering, and construction (AEC) sector. BIM is a commonly used and effective communication platform that enables the project team to design the building/infrastructure, monitor the construction work, and manage the facilities in an integrated manner. With the growing concern about the effects and depletion of non-renewable resources, BIM is also being increasingly adopted to predict and monitor the environmental impacts of construction. Past studies in the US have demonstrated that BIM can aid different areas of sustainable design and can support the LEED certification submission process. The application of BIM also allows project stakeholders, such as clients and designers, to share a single common source of information when addressing the difficulties of decision-making in the early design and construction stages.

BIM technologies are considered to provide an effective platform for attaining compliance with sustainability rating criteria. In the past few years, the application of BIM-based technologies in sustainability rating certification has attracted increasing research attention. For example, Barnes and Castro-Lacouture demonstrated that a total of 13 credits and one prerequisite in the LEED rating system can be directly calculated and documented by Autodesk Revit. Azhar et al. (2016, 2017) also examined whether LEED credits can be directly or indirectly prepared using BIM software and suggested that 17 credits and two prerequisites, which make up a total of 38 points, can be achieved by adopting BIM software (i.e., Autodesk RevitTM and IES Virtual EnvironmentTM). These include: four credit points in the sustainable site section; five credit points in the water efficiency section; one prerequisite and five credit points in the materials and resources section; one prerequisite and one credit point in the energy and atmosphere section; five credit points in the indoor environmental quality section; and one credit point in the innovation in design section (Wong and Kuan, 2014; Wong, 2015), (5 Ways Revit Supports Green Building, 2017) and (Olanrewaju et al., 2022).

2.7 Autodesk dynamo

Autodesk Dynamo was created in 2011 (see Figure 4). It is an open-source software influenced by Visual Programming Languages (VPLs), such as Grasshopper 3D for Rhinoceros 3D (Ferreira and Leitão, 2015). Its purpose is not only to generate graphical representations of complex geometries, but also to handle information flows between Revit and cloud services or a specific database in an efficient and autonomous manner (Salamak et al., 2019) and (Mahdjoubi, Brebbia, and Laing 2015) This enables users to efficiently build Revit tools without relying on programmers to provide the necessary plug-ins (Wong, 2015). However, Autodesk Dynamo may function without a Revit connection, despite its primary goal of increasing Revit's workflow as a plug-in by building a route into its essential core (McGinley and Fong 2015), (Sanhudo et al., 2016) and (Salamak et al., 2019).

3 Methods and materials

This study used a mixed methodology that combines qualitative and quantitative approaches. The first phase of this study focuses on reviewing the literature and collecting accessible data on the KSA's 2030 vision. Phase II intends to collect data from AEC professionals from an online survey. Furthermore, phase II of this research entails creating the BIM-Based model using Autodesk Revit and Dynamo. Phase III entails validating the model with a case study. A new BIM-Based model based on the data obtained would help achieve the water goal of the KSA 2030 vision. The validation model will be carried out on the basis of water savings and not on the basis of other criteria considered in Mostadam certification.

Figure 5 delineates an overview of the research methodology. It consisted of three phases. Phase I "basic database and review" included the use of literature where the scope identification databases were identified and the number of articles was determined, second the selection of relevant articles was determined, third abstracts were assessed, fourth number of excluded articles were determined, and finally key sustainability parameters were determined. The data were sourced primarily from academic journals, papers in conference proceedings, books, and articles from ongoing related projects. Phase II "BIM-Based" model involved the development of the BIM-Mostadam framework to measure KSA's 2030 vision attainment levels. Phase III "validation"

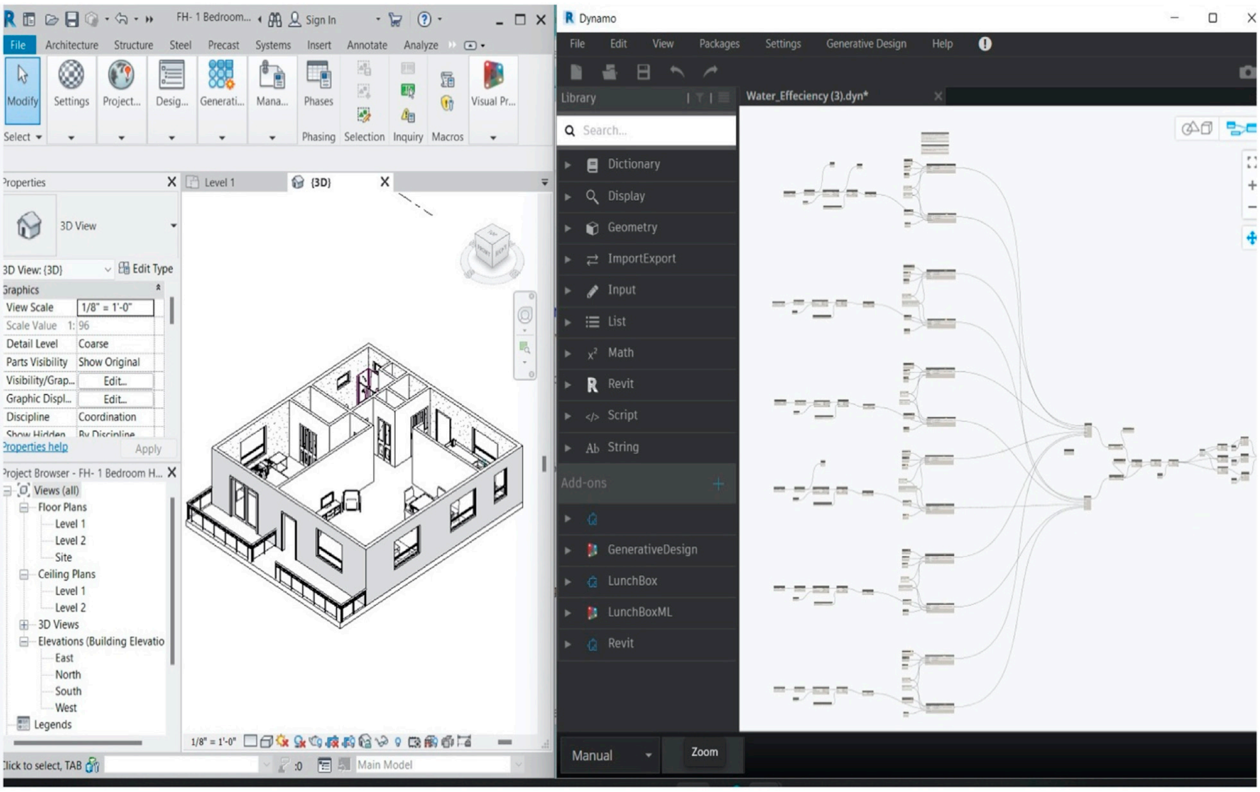

FIGURE 4
Revit and dynamo side by side (Author).

consisted of a survey about BIM's feasibility in the KSA and sustainability in the KSA, collecting data about three buildings asking about the type of these buildings and important aspect of these buildings in KSA, then integrating the findings in BIM, then selecting case studies and finally doing analysis and validation.

The following is a step-by-step roadmap of the methodology of this research:

3.1 Literature review

A literature review is conducted using the following keywords "KSA Vision 2030"; "BIM and Sustainability"; "BIM and Green Buildings"; "Building Sustainability"; "Sustainability in KSA"; "Green Buildings"; "Rating Systems in the Middle East"; "Benchmarks for Sustainability"; "Sustainability Framework"; "Sustainability Metrics."

3.2 Feasibility survey

Starting with a proof-of-concept survey. The data is gathered through Qualtrics, an encrypted and secured online host. The survey is forwarded to KSA builders, building owners, architects, contractors, and green consultants. This survey aims to explore the possibility of using existing BIM resources to promote the green building rating system Mostadam for certification of commercial and residential buildings. This research firstly looked into the actual needs, gaps and expectations in the industry regarding why and how applicable the integration of BIM and Mostadam rating system certification is in the KSA. The survey will gather views from AEC professionals on how feasible it is in technology and operation terms to integrate BIM. This survey also looks at what professionals expect and suggest this integration to be more than just an idea, a working process. The survey findings were used as a reference for the creation of the model.

3.3 Building information modeling-based application model

The development model of the BIM-Mostadam model is achieved using Autodesk Revit and Dynamo. The BIM-Mostadam model was created based on the match-up of the Mostadam credit

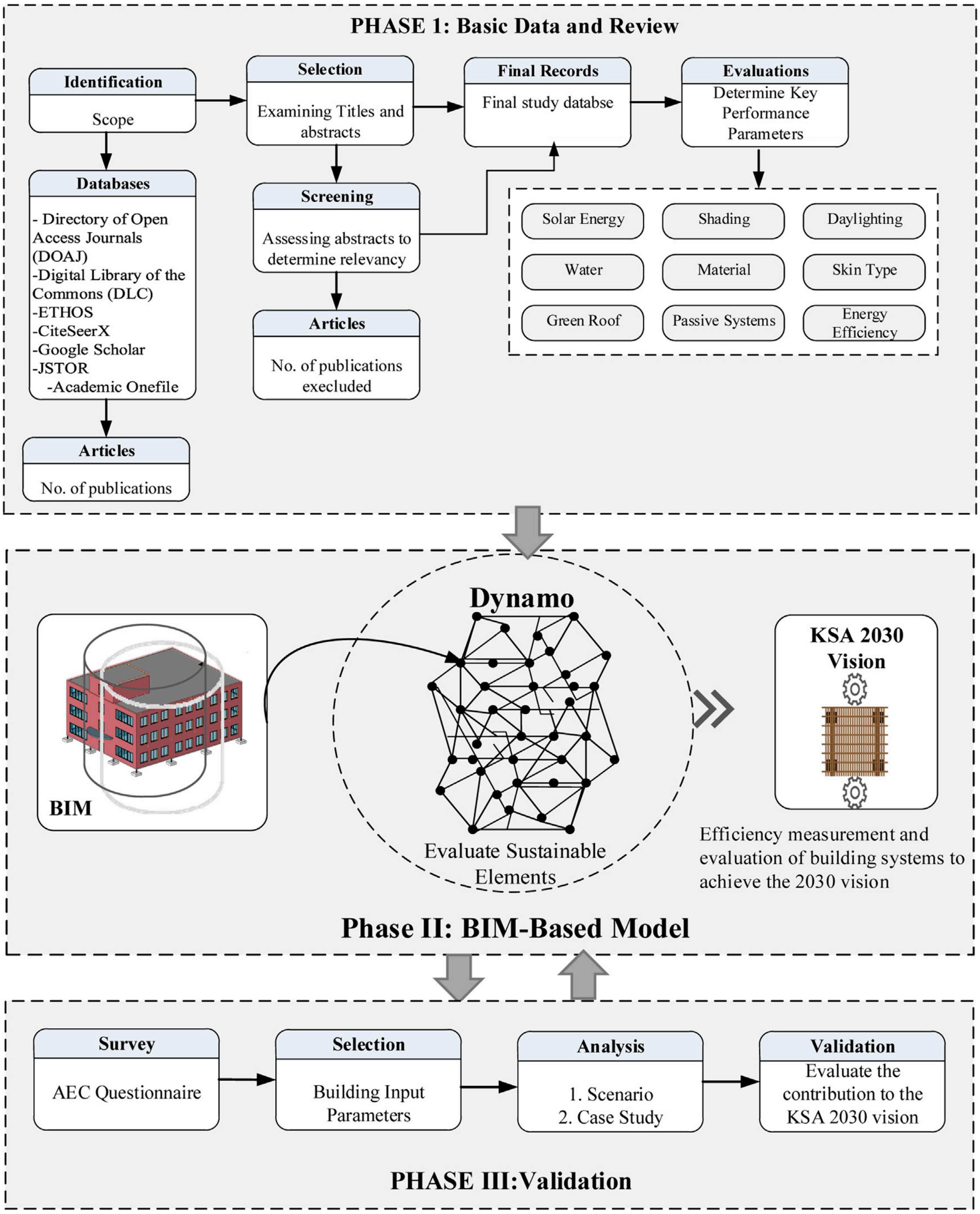

FIGURE 5
Overview of the research methodology (Author).

requirements and the functionalities available from current BIM solutions. For the purposes of this research, the Autodesk Revit software suite and Dynamo software application from Autodesk are being used.

3.4 Validation of building information modeling-based application model "case study"

The application model is validated by examining a case study. A case study was used to verify and validate the BIM-Based application model. All credits (including prerequisites) were analyzed and interpreted into data requests. Using Dynamo, a water plug-in was programmed into Revit to provide design assistance, and the total points of Mostadam certification were obtained. In addition, the total water saved was attained and compared to the baseline water consumption.

4 Dynamo building information modeling-based indoor water reduction model prototype

This section illustrates a step-by-step guide of the creation of the BIM-Based model focusing on the water category of Mostadam. Architects, engineers, designers as well as owners need to manage the complexity and all aspects of building sustainability to handle tools that are able to support them in the decision-making process. The more complex a facility is, the greater the complexity that dictates the distribution of resources.

Mostadam, the Saudi Arabian Green Building Rating System, is used in this context. Mostadam intends to adopt an iterative design approach, including stakeholders and specialists. It explains how to maximize the water use of a building facility, allowing for the careful conservation of this vital natural resource, which is becoming increasingly rare. The model is based on a match between the Mostadam credit requirements and the functionality available from current BIM solutions. This study utilizes the Autodesk Revit software suite and additional Autodesk software applications.

4.1 Indoor water use and reduction

Mostadam focuses on outdoor and indoor water consumption to decrease unnecessary water usage due to the operation and development within the built environment as well as increasing water efficiency. The goal of the Indoor Water Reduction prerequisite and credit is to minimize is to reduce the community's indoor water use through better design and appropriate technical solutions. The Mostadam rating system needs a minimum reduction of 20%. As a result, the first step is to install performing fixtures and fittings that can use 20%–60% less water than the established baseline. It is feasible to fulfill this goal by installing WaterSense labeled products or by following the Alternative Compliance Path, which attempts to demonstrate the reduction in indoor water usage by assessing a group of parameters provided on the Reference Guide and on the fixtures cut sheet. To develop the Dynamo Water Reduction plug-in, Mostadam's Rating System 2020 was used. Table 1 below illustrates the percentage reduction associated with the points reflected for Mostadam's Green Building Rating System.

TABLE 1 Points for reducing water (Mostadam Manual, 2019).

Percentage reduction	Mostadam points (O + E)
20%	2
40%	3
60%	3
Total	8

To demonstrate these savings, the following equation is utilized for each water fixture type:

Equation 1: Basic Indoor Water Uses Reduction Calculation (Mostadam Rating System, 2020) and (Dynamo Visual Programming, 2017).

$$\textit{Daily water use for each fixture type} = \text{Fixture flush or flow rate} \times \text{Duration of use} \times \text{Users} \times \text{Uses per person per day}$$

where,

- Fixture Flush: The data from a fixture should guide us through the "efficiency first" technique. It is measured in liters per minute or liters per flush. The period of use is not required in the second situation.
- Duration of use: the amount of time a user spends using a fixture in a single session.
- Uses per person per day: the number of times each fixture is typically used each day.
- Users: this number can be implemented as a design outcome or derived *via* an index (gross square meters per occupant).

Equation 1 must be used to calculate the baseline water consumption as well as the design case water consumption. The rate of reduction can then be calculated. The outcome will determine if the minimal requirement (W.E.—prereq.1) is reached and, finally, the points earned (W.E.- credit.2).

Equation 2: Indoor water-use reduction (Mostadam Rating System, 2020) and (Dynamo Visual Programming, 2017)

$$\%\,\textit{improvement from baseline} = \left\{\frac{\textit{Baseline Volume} + \textit{Performance Volume}}{\textit{Baseline Volumen}}\right\} X\,100$$

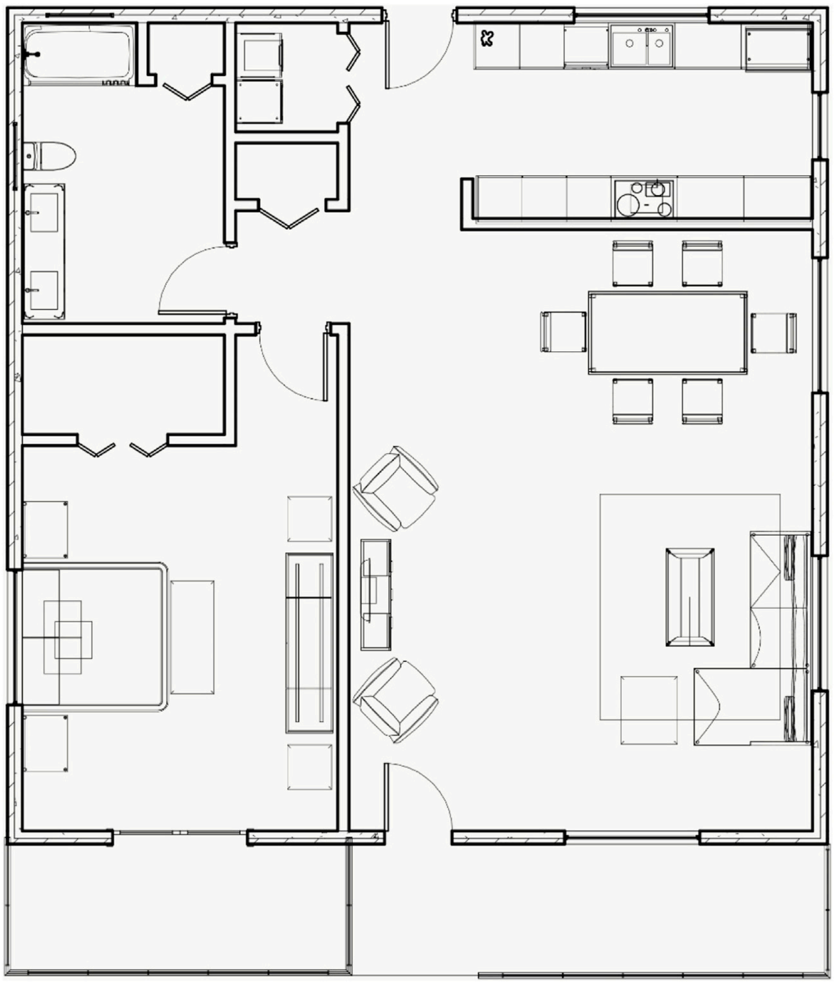

FIGURE 6
The floor plan example used in the study.

4.2 Revit and dynamo workflow: Implementing data and results checking

Water efficiency data clearly depends on fixture kinds and specifications, the building in which they are installed, and the occupancy rate. All of this information can (or should) be integrated into the building's BIM model, which should reproduce and supply all data linked to each discipline's components.

As a result, the hypothesis of having plumbing fixture information and a valuation of how many people will affect indoor water consumption is entirely credible. Starting with this basic data, the goal is to establish an automatic workflow that takes this data from the BIM model and processes it in order to validate the achievement of the thresholds stated in Table 1. Then, create a user-friendly BIM application that can apply Mostadam's calculations, requiring only a few simple inputs (included in the Mostadam Manual) and a geo-localized BIM model, which is required to investigate the computational design method.

4.3 Building information modeling-Mostadam application model

The first step is to "prepare" data within the BIM model so that it can be easily accessed and addressed once the computational design begins. This basic step necessitates a pre-design phase in which a rigorous organization (workflow strategy, parameters, steps...etc.) is required to prevent the most prominent barriers that may arise and, at times, force us to go back and restart with a new approach. The floor plan of the BIM model utilized in this investigation is depicted in Figure 6.

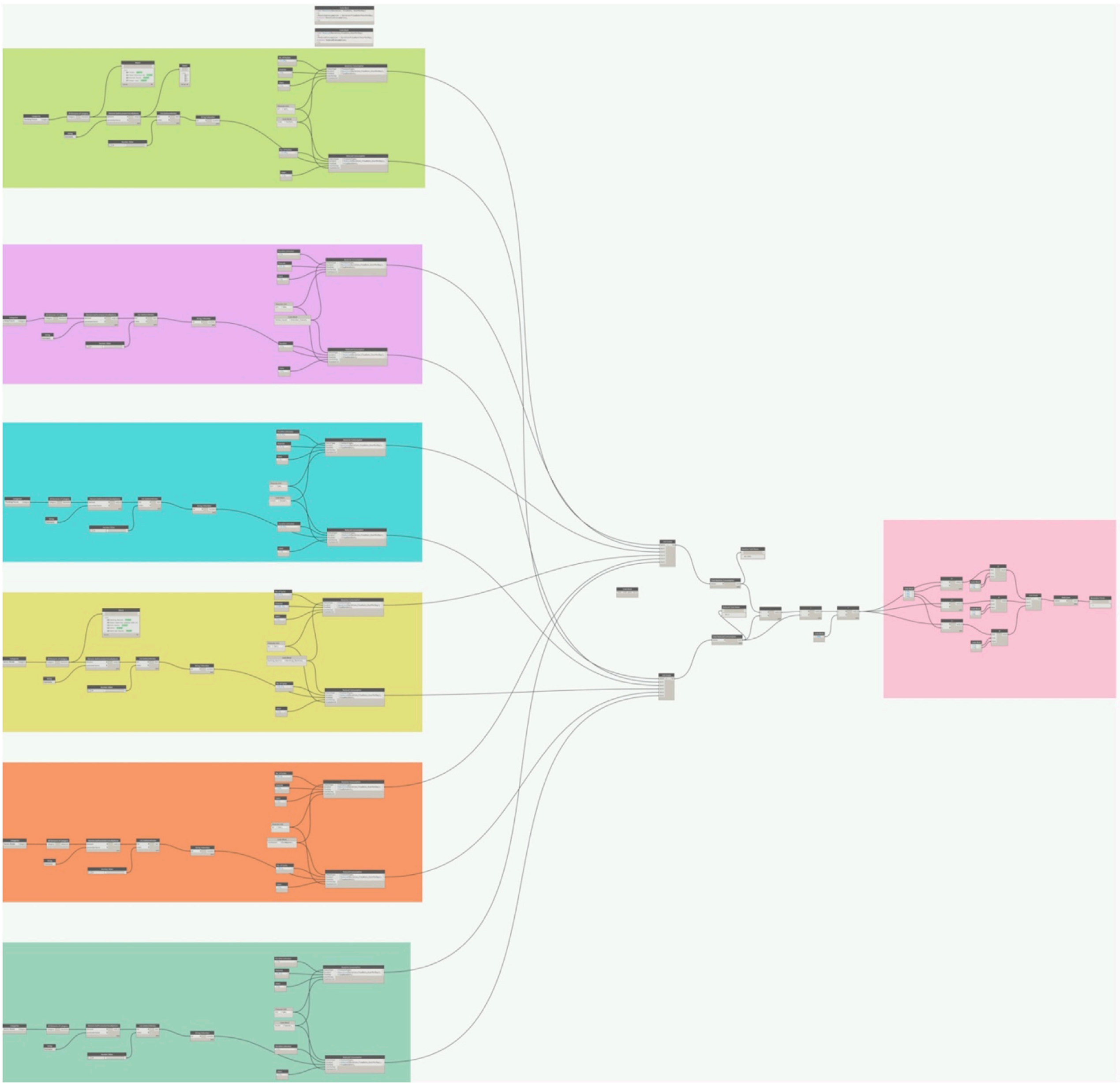

FIGURE 7
Overview of the base script.

As a result, beginning with generic plumbing fixture Revit families, we will employ the following technique to align the BIM model with the computational design workflow:

- Insert the type of the fixture into the "comments" parameter, such as "WC," "Faucet," "Shower," or "Kitchen sink," to avoid complications caused by the various family names that fixtures may have, which can lead to difficulties in collecting similar appliances (for example, a kitchen sink, a faucet, or a shower). However, the names of various shower fixtures could be different depending on the manufacturers who supply us with the<.rfa> file, the analytical plumbing data would remain the same.
- Take into consideration a parameter that is shared by all of the different kinds of fixtures, such as the location to insert flow data in order to facilitate the streamlining of the collecting phase in Dynamo using a pattern. [lpf: liter per flush (L); lpm: liter per minute (L/m)].

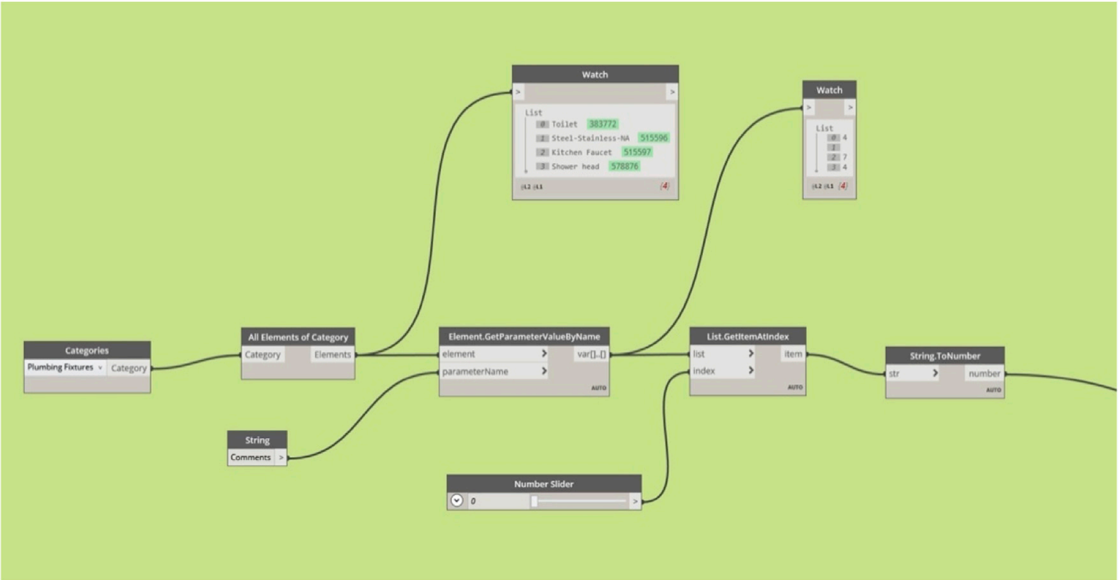

FIGURE 8
Detailed view of the toilet script (Part I).

- Make a valuation of building users by analyzing apartment composition.

The case study was created *via* Autodesk Revit. It is a one-bedroom home intended for two users. This case study was created to showcase the amount of water saved when using the Dynamo Water Reduction plug-in. The Case study highlights the amount of water saved when using the plug-in compared to the baseline water used and translated that into Mostadam certification points.

4.4 Dynamo: Collecting data and performing the script

The dynamo script can be started once the approach has been determined. The expected result is similar groups of nodes, one for each type of fixture, from which the actual performance (Revit parameter) and baseline performance (Mostadam's table inputs) can be calculated; to complete the formula, the following should be implemented: users (given data), uses per day, and, if necessary, duration of use (see Figure 7).

To streamline this step, you can edit a custom node that allows you to complete only the fundamental inputs, resulting in a faster and smarter workflow that is easier to control and utilize (see Figure 8).

Following the application of this workflow to each plumbing fixture in the Revit model, the results must be added and compared to determine the percentage of improvement required by the Mostadam procedure. It is possible to compute points earned directly in the BIM model using this dynamo script (see Figures 9–11).

5 Results

This section addresses the results and findings of this study. It highlights the factors of BIM that should be addressed to promote green building adoption that aligns with the KSA's 2030 vision. Based on relevant literature indicated that there are some critical aspects and challenges which have resulted in a low number of registered projects and buildings in Saudi Arabia—for instance, international sustainable building rating systems do not take into account regional differences and microclimates. The results for research questions 1, 2, and 3 are addressed by combining inferences from the literature review, survey, a case study, and the development of the BIM-Based model.

5.1 Research questions 1

5.1.1 RQ1: How can Mostadam be used to measure the attainment of the KSA 2030 vision?

Based on the review of literature and data collected from the survey and the model developed, Mostadam helped in the attainment of the KSA's 2030 vision by creating:

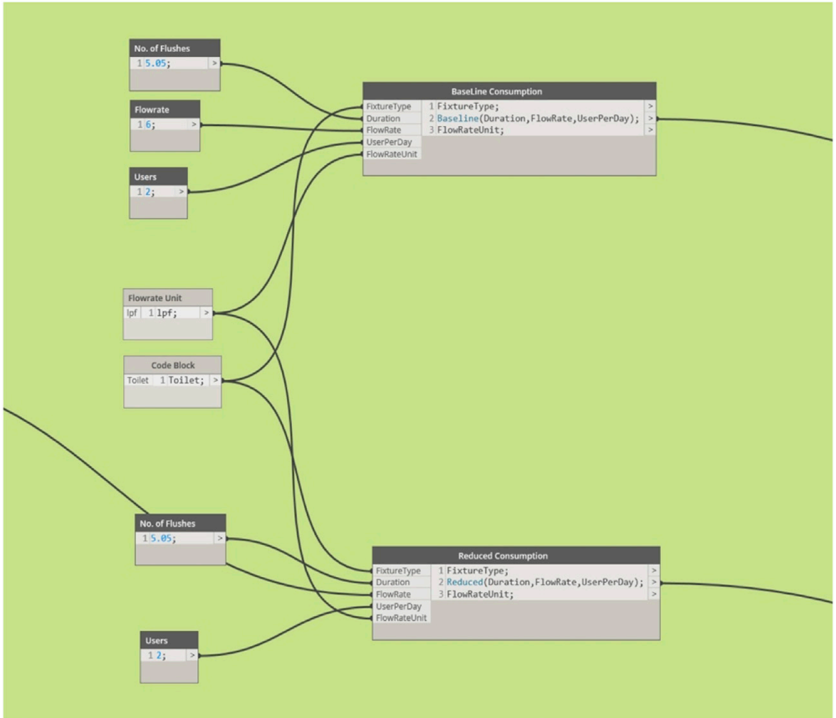

FIGURE 9
Detailed view of the toilet script (Part II).

- More sustainable buildings and infrastructures in KSA.
- Moving the Kingdom from its dependence on oil towards the use of its natural resources and renewable energy.
- Mostadam was an inspiration for KSA's vision 2030; their goal perfectly aligns and supports one another.
- The Dynamo plug-in reduced the water consumption in the case study provided in comparison to the baseline consumption.

Looking at Table 2. We can see the top priorities of the Mostadam green building rating system which are (water conservation, promoting energy, human health and comfort, improving waste management, and reducing environmental impact of construction practices) are also the top priorities and the core of the KSA's 2030. They perfectly align and support one another. From Table 2 the following remarks and comments are identified:

- The KSA 2030 vision aims to promote the optimal use of water resources by utilizing renewable and treated water and eliminating desertification aligns with the Mostadam water goal.
- The KSA 2030 vision goal of achieving maximum efficiency aligns with Mostadam Energy's goal.
- The KSA 2030 vision seeks to enhance all aspects of the Saudi population's development and well-being and aligns with Mostadam's Human Health and Comfort goals.
- The KSA 2030 vision goal of enhancing the effectiveness of waste management aligns with Mostadam's Improve waste management goal.
- The KSA 2030 vision goal of establishing major recycling projects and rehabilitating aligns with Mostadam reducing the environmental impact of construction practices.
- Even though the KSA 2030 vision goals of safeguarding beaches and natural reserves and islands, making them accessible to everyone, and reducing all types of pollution, it does not have a direct alignment with the Mostadam rating system. They are still considered a significant part of the Mostadam rating system. The purpose of this green building rating system is to preserve natural resources and reduce pollution.

The KSA 2030 vision aims to make Saudi Arabia an ideal sustainable society by reducing its reliance on petrol, creating more sustainable buildings and infrastructures, and achieving sustainability in all aspects of life, especially in the residential and commercial buildings and sustainable city sectors. Currently, there is a notably low number of certified green buildings in Saudi Arabia compared with other Gulf countries, and the rate of change is too slow, especially with climate change and the oil

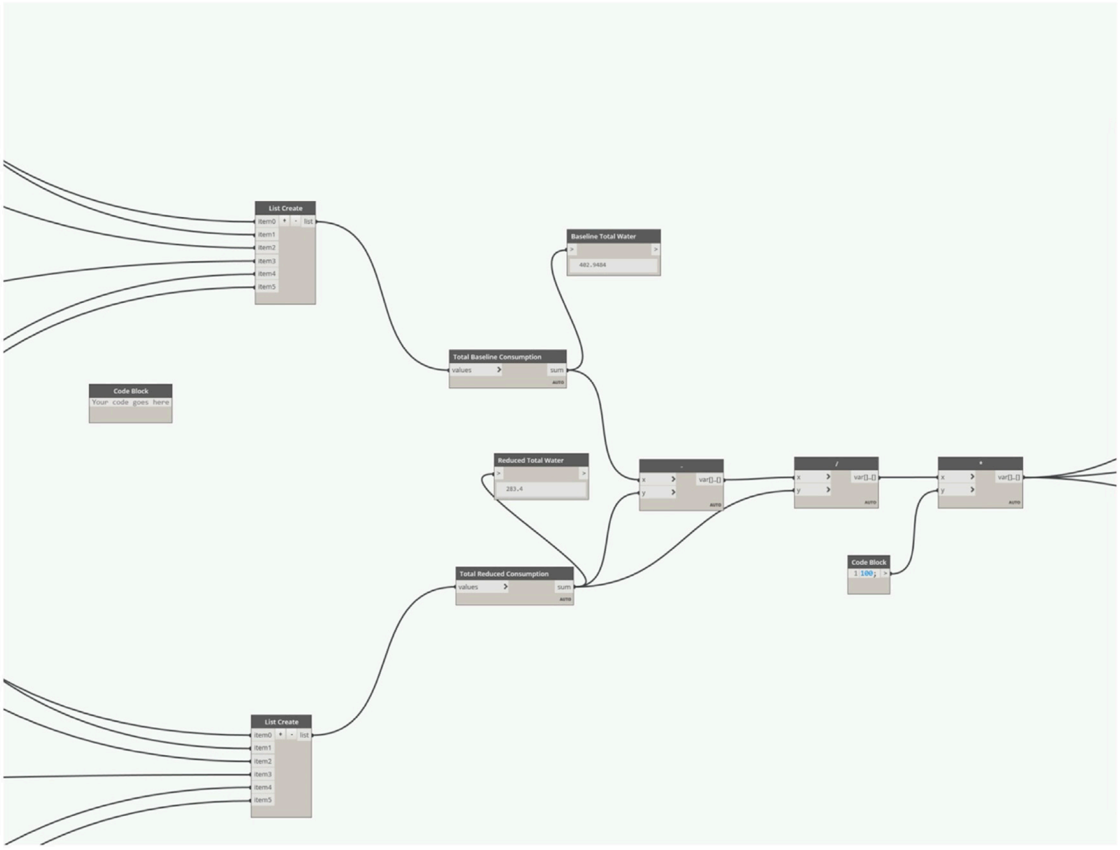

FIGURE 10
Part of dynamo script for Mostadam water reduction.

shortage. However, Mostadam was recently launched. Mostadam was an inspiration of KSA's 2030 Vision. It is a rating system used to evaluate existing and new residential and commercial buildings to assist in achieving more green buildings in Saudi Arabia. Integrating BIM's abilities and capabilities will help accelerate the Mostadam certification process and create more sustainable buildings in Saudi Arabia, which will achieve the best effect on far-reaching advancement in Saudi Arabia to accomplish KSA 2030 vision.

5.2 Research questions 2

5.2.1 RQ2: How can Autodesk Revit be utilized to assist the Mostadam certification?

BIM technologies provide an important platform to meet requirements for sustainability ratings. Previous studies in the United States showed that BIM could help in various sustainable design areas and support the process of submitting LEED certification. BIM also helps project stakeholders, such as customers and designers, share a shared source of knowledge when discussing early design and construction decisions (Jalaei & Jrade, 2015). In recent years, research attention has increasingly paid attention to the application of BIM technology in the sustainability rating certification. In particular, Barnes and Castro-Lacouture showed that Autodesk Revit could directly measure and record a total of 13 credits and one prerequisite in the framework of LEED ratings. In addition, Azhar et al. investigated whether LEED credits can be prepared with BIM software directly or indirectly and recommended the adoption of BIM software to obtain 17 credits and two conditions that makeup 38 points in total (i.e., Autodesk RevitTM and IES Virtual EnvironmentTM) These include:

- Four credit points in the sustainable site section;
- Five credit points in the water efficiency section;
- One prerequisite and five credit points in the materials and resources section;
- One condition and one credit point in the energy and atmosphere section;
- Five credit points are in the indoor environmental quality section, and one credit point is in the innovation in design section (Wong and Kuan, 2014).

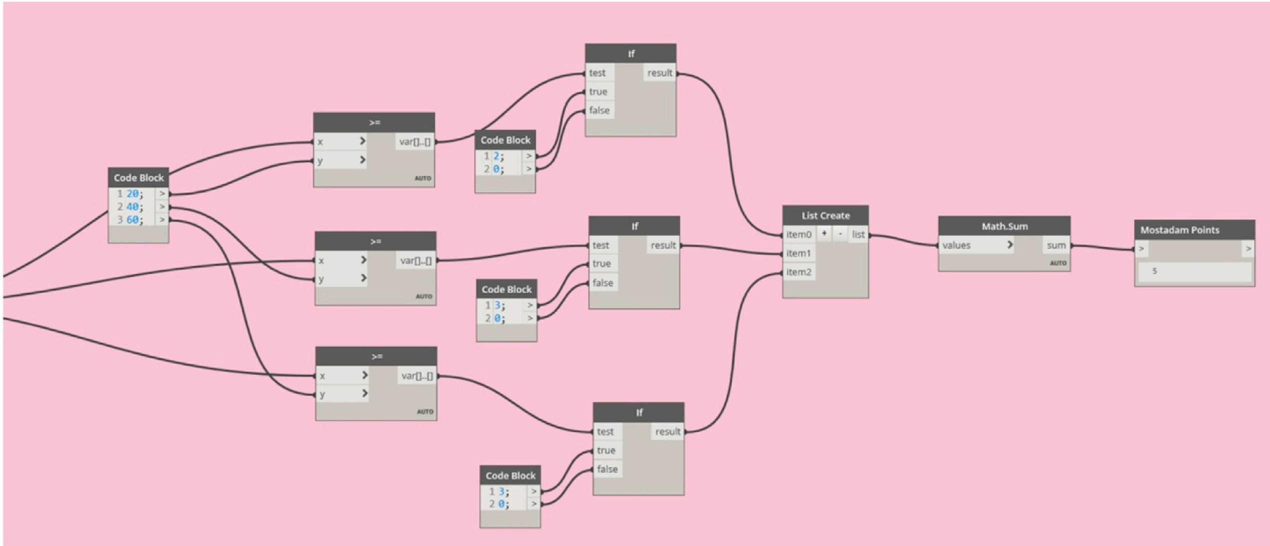

FIGURE 11
Part of dynamo script showing the computation of Mostadam point earned.

TABLE 2 A table comparing the main elements of KSA's 2030 vision and Mostadam (Mostadam Rating System, 2020) and (Dynamo Visual Programming, 2017).

Main elements of KSA's 2030 vision	Mostadam rating system priorities	Mostadam direct alignment with KSA 2030 vision ✅
1. Promoting the optimal use of water resources by utilizing renewable and treated water as well as eliminating desertification	1. Water conservation	✅
2. Achieve maximum efficiency	2. Promote energy	✅
3. Enhance all aspects of the Saudi population's development and well-being	3. Human health and comfort	✅
4. Enhancing the effectiveness of waste management	4. Improve waste management	✅
5. Establishing major recycling projects, rehabilitating	5. Reduce the environmental impact of construction practices	✅
6. Safeguarding beaches and natural reserves and islands and making them accessible to everyone		
7. Reducing all types of pollution		

Several plug-ins exist today showing how Autodesk Revit can aid in achieving LEED green building certifications, including:

- The Automated Daylighting plug-in for LEED is a new feature in Lighting Analysis for Revit. It performs extremely fast and physically accurate daylighting simulations in the cloud, delivering results for LEED IEQc8.1 2009 directly to the design environment. The service automatically generates the information you need for submission to the GBCI (Autodesk Apps for LEED Automation, 2021).
- Autodesk Revit Insight 360 plug-in that runs analysis for illuminance and validation of LEED v3 IEQc8.1 and LEED v4 IEQ Daylight Credit, Option 2 (Crea, 2017).

Autodesk Insight empowers architects and engineers to design more energy-efficient buildings with advanced simulation engines and building performance analysis data integrated into Revit. Insight improves energy and environmental performance throughout the building lifecycle (see Table 3). It combines energy, lighting, and solar analysis for a holistic approach to creative performance design (Autodesk, 2017).

Based on past studies and literature, it has been evident that Autodesk Revit plug-ins such as Insight can help attain and accelerate LEED certification and provide better building performances. As a result, incorporating Autodesk Revit plug-ins with the Mostadam rating system will aid in the Mostadam certification process and therefore result in attaining more green buildings in the KSA.

5.3 Research questions 3

Answering question 3 is addressed by combining inferences from the literature review, survey, a case study, and the development of the BIM-Mostadam model.

5.3.1 RQ3: How can BIM be utilized to integrate the objectives of the KSA 2030 vision within the Mostadam rating system?

- Survey-The survey results were used as a guideline for more in-depth development of the BIM-Based model.

These results build on existing evidence from the AEC professionals about BIM, Mostadam, and the 2030 Vision. Upon receiving the results from the survey, it was evident that the majority of the participants were very experienced. Figure 12 below shows that 60% of the participants had more than 10 years of experience in the field. Another key demographic information gained from the survey was the participants' educational background. Figure 13 shows that the majority of the participants were architects 32%, 15% were from a construction management background, 14% were from a sustainability and green design background, 10% were electrical engineers, 6% were mechanical and electrical engineers, and 23% were from other experiences such as (urban planners, instructors, interior designers, interior architects, professors, and faculty members at universities).

To validate the overall level of awareness of the respondents, they were first asked about their knowledge of the basic definition of green buildings. A total of 100% of the respondents answered "YES" to the question of whether or not they had heard of a green or sustainable building. Furthermore, of the total 200 participants, 180 respondents had heard of the LEED and Mostadam rating systems, which was about 80% of the total respondents. The level of awareness in the general public and stakeholders has previously been studied, and several publications share the same results, which indicate that even though the level of awareness is still not at the desired level to some, it is still rising, and more efforts are needed to increase the level in the general public.

Moving to more focused building type questions, the participants were asked about their knowledge of the Mostadam rating system on new or existing buildings (Figures 14, 15) and whether they would be willing to use the Mostadam rating system on new or existing structures. The question states: "What is your knowledge and level of experience about Mostadam? 33% of the participants just heard about it, 43% plan to use it, 14% in one project, and 10% in more than one project.

Even though the KSA's local green building rating system, Mostadam, is available to use, it is still in its infancy compared to LEED. This lack is because Mostadam was recently launched, and it is not widely spread in the country. However, Mostadam still showed strength and acceptance to be used in conjunction with LEED. More than 40% of the selected the preference of using both rating systems, and this will substantiate the result respondents selected the importance of using both rating systems, and this will from the question on the level of awareness of the respondents to the concept of green and substantiate buildings.

- The BIM-Mostadam Application Model was designed based on matching the Mostadam credit specifications and the functionality of current BIM solutions. The Autodesk Revit software suite and an additional Autodesk Plug-in application are used for this study.

TABLE 3 A table showing the Autodesk Revit insight plug-in (5 Ways Revit Supports Green Building, 2017).

Green building rating system	Build-in energy analysis extension/Plugin/Software	Sustainability criteria	BIM package and vendor company
LEED LEED v3 IEQc8.1 and LEED v4 IEQ Daylight credit, Option 2	Insight 360	Energy Analysis Tool can be used for 1. Lighting analysis 2. Solar analysis 3. Energy analysis	Revit (Autodesk)

FIGURE 12
Years of experience.

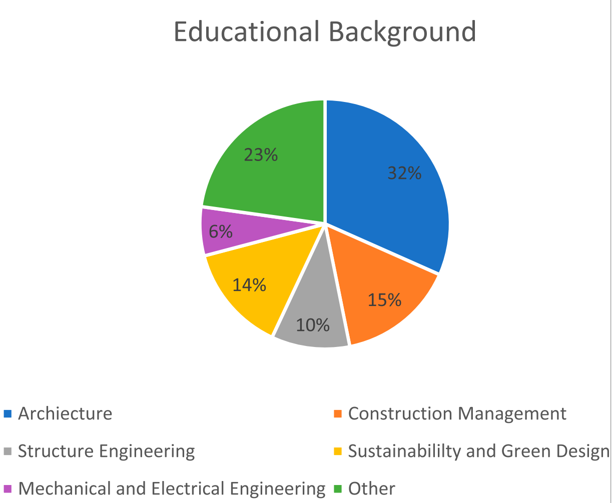

FIGURE 13
Educational background.

The plug-in specifically targeted the water category of Mostadam's Green Building Rating System.

- A case Study-was used to verify and validate the BIM-Based model and the water savings were apparent when using the plug-in compared to baseline water consumption.

6 Discussion

The primary goal of this study is to develop a BIM-Based model for sustainability in the Kingdom of Saudi Arabia (KSA) to achieve the KSA's 2030 vision. This research attempts to look at the integration of BIM and green building from a systematic perspective, using the Mostadam rating system and the Mostadam certification as a unique case. The BIM plug-in was specifically used to measure the "water" category from the KSA's 2030 vision and the water impact category of Mostadam's.

Based on the literature review and the data collected from the surveys, various challenges exist affecting the attainment of green buildings in Saudi Arabia, including environmental factors. Because of the harsh arid climatic conditions of the country, these environmental factors must be considered in the design of a sustainable Saudi building. The literature showed that after the country's "oil-boom" phase, the design of Saudi buildings was sadly and irrationally mimicking Western-housing designs. This shift in design practices not only neglected the cultural needs, as discussed earlier but neglected the environmental needs that resulted in the vast sums of energy consumed to cool the indoor environment. Several environmental factors were extracted from the literature review, including:

- Passive cooling
- Energy saving
- Water insulation (interior insulation)
- Water conservation
- Thermal insulation
- Thermal comfort
- Landscape
- Site orientation.

Moreover, the issues related to sustainable building materials and techniques in the Saudi construction industry need to be considered. All these factors indicate the need to develop local rating systems such as Mostadam.

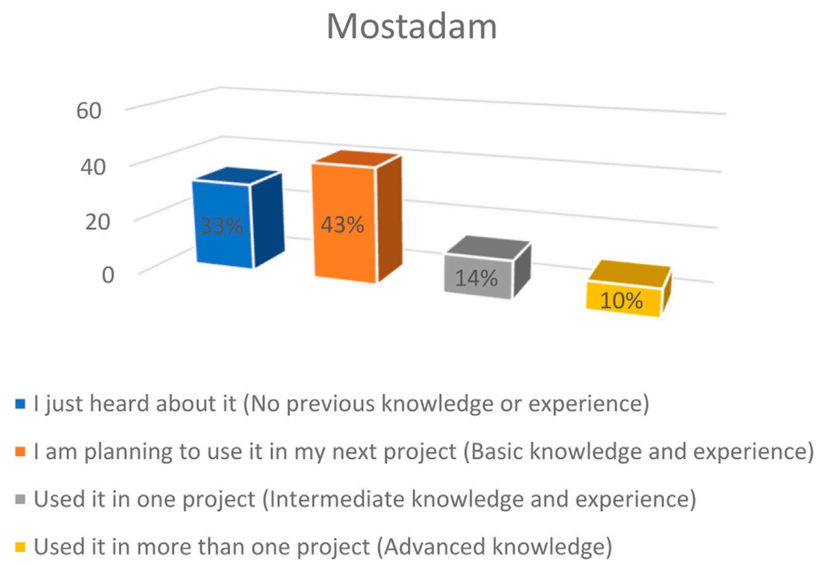

FIGURE 14
Knowledge and level of experience about Mostadam.

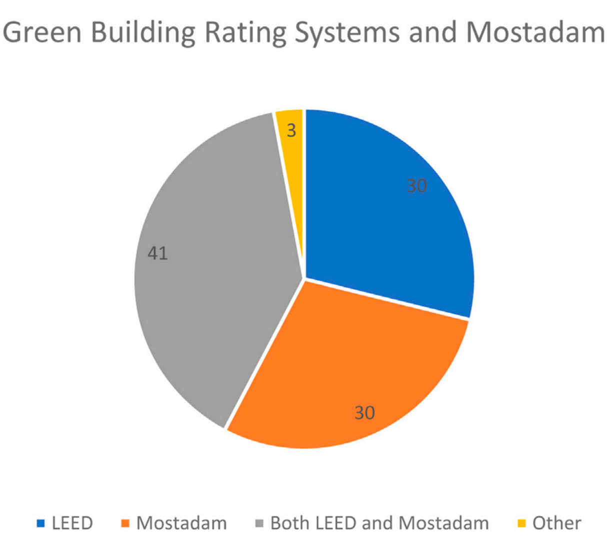

FIGURE 15
LEED, Mostadam, and other rating systems in KSA.

7 Conclusion

Building Information Modeling (BIM) can significantly aid in developing a unified building performance analysis to ensure a more sustainable building design. BIM and green buildings are two main factors in the AEC field. Additionally, this research acknowledges factors of BIM that should be addressed to promote green building adoption that aligns with the KSA's 2030 vision. Recent literature indicated that some critical aspects and challenges have resulted in a low number of registered green projects and buildings in Saudi Arabia. For instance, international sustainable building rating systems do not consider regional differences and microclimates. As a result, it is essential to develop local rating systems such as Mostadam.

This research acknowledges BIM and green buildings as the two major trends in the AEC industry. Based on that premise, it proposes a new strategy for the AEC professionals to achieve a green building certification such as Mostadam through integrating BIM and green building rating systems. In response to the research goals, the first step was to conduct a feasibility analysis survey to investigate the two most fundamental questions in the BIM and Mostadam integration: 1) What does Mostadam require; and 2) What BIM can provide to achieve the KSA 2030 vision.

Based on Saudi Arabia's vision 2030 for achieving sustainability in all aspects of life, especially in the residential and commercial buildings and sustainable cities sectors, the "Mostadam" rating system was recently launched to evaluate existing and new commercial and residential buildings. This can be considered a result of the notably low number of certified green buildings in Saudi Arabia compared with other Gulf countries. This research uses a survey to examine the present status of sustainable structures in Saudi urban communities. The study aims to develop a BIM-Based application model to assist in implementing the Mostadam rating system. The proposed model seeks to achieve the sustainability aspects of the Mostadam green rating system and certification while supporting the KSA's 2030 vision. The suggested model is validated by the data collected from the survey and a case study.

The current rate of gasoline supply in the Kingdom of Saudi Arabia is unsustainable. As a result, the Kingdom established its 2030 vision to solve this issue. The 2030 vision seeks to make the KSA a more sustainable society by reducing its dependency on fossil resources. Even though green buildings are being built in many countries worldwide, they do not have the same recognition and acceptance in Saudi Arabia. The absence of rules and regulations promoting the country's sustainability and green buildings has revealed this gap. Due to the low number of green buildings in Saudi Arabia, this study intended to develop a new BIM-Based model for Sustainable Built Environments in Saudi Arabia that meets the Kingdom's 2030 vision, specifically water conservation. The Dynamo plug-in is able to calculate water saved/reduced compared to the baseline water consumption and transform that into percentages of reduction. Based on the rate of reduction (20%–60% from baseline consumption), the points earned towards the Mostadam Green Building rating system can be calculated. Therefore, the BIM-Based application model can improve sustainability in the KSA by reducing water consumed and translating that into points earned towards the Mostadam Green building rating system which supports and aligns with the KSA vision of 2030. The Saudi Vision 2030 has set a plan for future generations to succeed and live in a stable economic environment in which the private and governmental sectors collaborate to increase the country's income and natural resources. As a result, Mostadam and the KSA vision 2030 can be attained using the proposed BIM-Based application model.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

FH and NN: Substantial contributions to the conception or design of the work; or the acquisition—analysis or interpretation of data for the work—drafting the work or revising it critically for important intellectual content; provide approval for publication of the content—agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Revisiting the dynamics of car cabin environment and driver comfort

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Revisiting the dynamics of the car cabin environment and its impact on driver comfort is essential, as these concepts have not been explored in recent years. Older methods of assessing driver comfort and cabin environments require elaborate experimental settings and prolonged engagement of study participants, making repeatability difficult. Therefore, this study develops a model for study models the car cabin environment based on temperature, humidity, and CO_2 levels using a thermal imager, an air quality device, and open-source temperature and humidity data. This study also determines whether the impact of the cabin thermal environment on driver comfort (skin dryness, eye fatigue, body fatigue, and body heat) can be quantified based on driver perceptions. The study results showed that body fatigue decreased from 4.2 to 2.7 when the average relative humidity is reduced from 37.2% to 24.2%, and the temperature dropped from 41.8°C to 40.0°C. Notably, the impact of air temperature on the cabin thermal environment was 1.8 times stronger than that of the car skin temperature. Cabin temperature was found to be a better predictor of driver (dis)comfort than cabin humidity and CO_2 levels. A 10 min exposure to summer heat in the UAE was found to have a significant effect on drivers' perceptions of body fatigue, body heat, and eye fatigue. Overall, these findings have implications for car cabin ergonomics and future thermal comfort research.

KEYWORDS

cabin environment, driver comfort, thermal camera, likert scale, linear regression

1 Introduction

Studies concerning rising heat in urban areas seldom discuss its impact on car cabins and drivers (Joubert et al., 2011; Nakano and Tanabe, 2020; Marcotullio et al., 2022). For example, Nakano and Tanabe (2020) investigated the thermal impacts of air-conditioned (AC) and non-AC spaces on occupants, focusing exclusively on the heat characteristics of the built environment. Similar studies on the heat impacts of AC and non-AC car cabins on drivers have not been discussed in the relevant literature. This selective focus has led to the literature that proposes heat management strategies disconnected from driver needs. For example, one study presented how to determine optimal tree placement to mitigate urban heat (MacLachlan et al., 2021). Another study proposed enhancing basic services, infrastructure, awareness, and education among residents to enhance urban heat management practices (Adegun et al., 2022). A driver-centered approach to the impacts of urban heat is lacking in the literature.

Overheated vehicle cabins cause, on average, 37 child deaths per annum in the United States (Horak et al., 2017). High humidity in the car cabin can affect driver concentration, situation handling, eye comfort, and visual fatigue (Tsutsumi et al., 2007). Because CO_2 concentration in the car cabin is associated with driver fatigue (Mathur, 2016), the in-cabin environment has implications for driver health and comfort, but studies have neglected this underlying relationship. Crizzle et al. (2017) searched several renowned databases (Pubmed, CINAHL, Scopus, and PsycINFO) for articles on the health and wellness of truck and bus drivers in Canada and the United States; their analysis of 33 peer-reviewed articles published between 2000 and 2017 revealed that smoking, obesity, hypertension, poor diet, lack of exercise, stress, and sleep were evaluated as major problems for drivers (Crizzle et al., 2017). This exclusion of the cabin environment impact from the literature on driver health and comfort could undermine the significance of regulating cabin environment. Policymakers, fleet managers, and drivers might disregard the cabin thermal profile and air quality.

Summertime temperatures in the UAE can reach 51°C, uncomfortable to remain outdoors. The effects of this heat level on workers in the construction and oil and gas industries have been well documented in the literature (Siddique et al., 2019). Comprehensive programs to reduce heat-related illness for workers in the UAE and other Middle Eastern countries exist (Joubert et al., 2011). However, the effects of heat on car drivers are typically disregarded based on the assumption that car ACs are sufficient to offer the appropriate degree of comfort. Instead, the focus is almost exclusively on 'at risk' workers, such as farmers, construction laborers, firefighters, miners, soldiers, and proletarians (Xiang et al., 2014). This neglect has resulted in a lack of engineering and administrative control measures to reduce drivers' exposure to heat. The use of complex experimental settings in previous studies (Tsutsumi et al., 2007; Mathur, 2016) could have contributed to a lack of research on driver comfort and the cabin environment. For example, Tsutsumi et al. (2007) required study participants to sit in a climate chamber for 5 h to evaluate the impact of the cabin environment on their comfort levels. Finding volunteers to sit for that long in a controlled environment, even when it is pleasant, is difficult. Creating a climate chamber may also not be feasible in many cases. Thus, introducing simpler and more intuitive methods to profile the car cabin environment and its impact on driver health can encourage more scholars (or policymakers, for that matter) to participate in this research domain.

This exploratory study has two main goals: (i) to revisit the dynamics of the car cabin environment in the context of hot UAE summers, and (ii) to demonstrate the usefulness of a simpler, psychometric approach to evaluate the impact of cabin environment on driver comfort. The study assumes that the cabin environment can be modeled using external factors such as car skin temperature, air temperature, and air humidity. Thermal conditions (temperature and relative humidity) and air exchange (CO_2 concentration) are considered the main attributes of the cabin environment (Croitoru et al., 2015; Szczurek and Maciejewska, 2016). The impact of these factors–temperature, relative humidity, and CO_2 concentration–on driver comfort is evaluated using four constructs: body fatigue, eye fatigue, body heat, and skin dryness. These constructs are widely regarded as measures of driver comfort (Tsutsumi et al., 2007; Danca et al., 2016). This study is expected to contribute to the literature on car cabin thermal dynamics and associated driver comfort levels. This study is novel because it explores the impact of cabin thermal environments on driver comfort, which has remained unexplored in the context of the UAE, despite the country's soaring levels of heat witnessed during the summers. The use of real field settings, as opposed to climate chambers to elicit more accurate driver responses is another innovative aspect of this study. The latter (climate chamber) methodology, used in most studies concerning cabin environment and driver comfort, does not mimic real-life situations wherein car users (while walking to the parking lot) face external environmental heat before experiencing the cabin thermal environment. This pre-exposure to heat might affect how drivers rate their cabin environment. Finally, this study simplifies existing research methods for assessing the drivers' comfort level by employing fewer instruments and relying more on psychometric approaches based on statistical analysis to explore the relationship between cabin environment and driver comfort.

2 Materials and methods

The overall objective of this study is to measure the impact of external thermal conditions, including car skin temperature, on the cabin thermal profile, and relate it to driver comfort. The air conditions outside the cars are expected to affect the air conditions inside the cars, thereby affecting driver experience (level of comfort). Because car ACs can alter cabin conditions (temperature and humidity), drivers' experiences before and after turning on the ACs are evaluated. Exposure to non-AC conditions would help simulate the external environment conditions that drivers face while walking to and from the car parking. While long-term (more than 15 min) exposure to high-temperature levels can induce heat stroke, little is known about the impact of short-term heat exposure.

This study included a car cabin and driver comfort monitoring experiment, conducted on 26 May 2022, at the UAE University visitors' parking area located in Al Ain city, UAE. The experimental settings included ten white cars parked under different shading conditions: eight under an

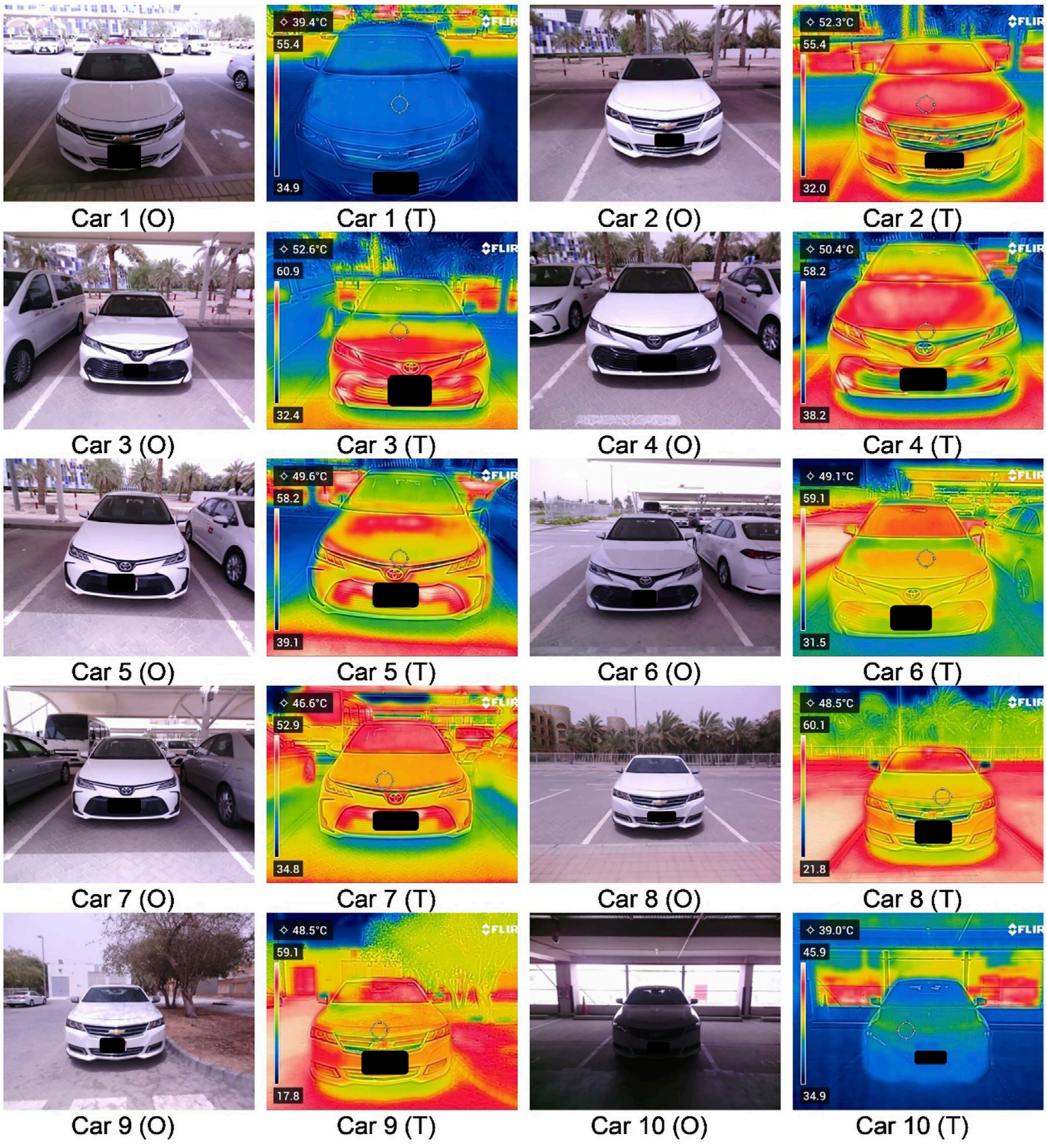

FIGURE 1
Optical and thermal images of cars parked under various shading conditions.

outdoor covered parking lot, one under a tree, and one in an indoor parking compound. Different shading conditions were meant to introduce random variation in the car cabin thermal environment. All cars had the same (white) color to rule out the reported impact of car color on the cabin thermal profile (Levinson et al., 2011). Because car materials can impact the cabin thermal environment (Marshall et al., 2019). Cars of similar make and model were used in this experiment to neutralize this effect. All cars were gulf variants of standard sedans of Japanese origin. At random periods during the day, the research team visited each car individually to monitor the car skin temperature and cabin air quality (temperature, humidity, and CO2 levels). A handheld thermal imager was used to photograph the cars (Figure 1). Because various components of the car body showed different temperatures, for the sake of consistency in recorded values, the temperature of the hottest part of the car skin was recorded.

Car cabin temperature and humidity levels were measured using an off-the-shelf air quality monitor. The device could log temperature and humidity levels at 10 s intervals. The surrounding air temperature and humidity levels were retrieved from an open-source metrological data repository that records weather data at hourly resolution (Weatherspark,

TABLE 1 Thermal profiling of car skin, car cabin, and the surrounding air.

Car no.	Car skin temperature (T_s)	Cabin humidity (H_c)	Cabin temperature (T_c)	Air humidity (H_a)	Air temperature (T_a)
1	38.0	40.0	35.0	41.0	32.0
2	48.5	35.2	40.0	37.0	33.0
3	51.0	46.2	38.6	32.0	34.0
4	51.6	39.8	39.5	28.0	35.0
5	53.7	45.2	41.5	22.0	38.0
6	47.8	39.5	43.0	17.0	39.0
7	47.7	37.7	41.9	15.0	40.0
8	50.6	29.6	50.0	12.0	40.5
9	47.3	28.0	49.7	11.0	41.0
10	37.7	30.3	38.7	11.0	41.0
Mean	47.4	37.2	41.8	22.6	37.4

2022). The temperature was assumed to remain constant throughout each hourly interval. Table 1 shows the thermal properties of the car skin, car cabin, and surrounding air. Note that the cabin humidity (H_C) and cabin temperature (T_c) values show the averages of 5 minutes of data logged for each car (Table 1).

To measure the impact of cabin air quality on driver experience, two study participants were assigned per car to sit in the front seats for 10 min. The car AC was kept off for the first 5 min and on for the last five. Moreover, the car windows were kept closed during the experiment. In total, 11 participants participated in the driver perception survey: ten respondents (one per car) and one surveyor (the same person for all ten cars). The reason for assigning a different participant each time was to ensure that the study participants did not face heat-related illnesses such as heat exhaustion, or worse heat stroke, which could set in after 10–15 min of exposure to the heat levels observed in the UAE. The surveyor, who had to successively sit in all ten cars, was protected from the heat by limiting his sitting time to that part of the experiment when car ACs were turned on. Notably, the participants were told that they could leave the car (or turn on the AC) at any point during the experiment, should the cabin environment start feeling too hot. The purpose was to record the impact of changing thermal conditions on driver comfort. Apart from H_c and T_c, the cabin-CO_2 (C_C) levels were also logged to understand the impact of CO_2 concentration on driver comfort. The comfort level was measured in terms of body fatigue, eye fatigue, body heat, and skin dryness, using a five-point Likert scale where one meant the least impact and five meant the greatest.

Table 2 shows the passenger experience data under varying car cabin conditions. Each case includes 5-min average cabin air quality data with a corresponding passenger comfort rating. Humidity was measured in relative %, the temperature in °C, and CO_2 in parts per million. In total, there were 20 cases, and data were collected at various times of the day.

3 Results

Data analysis (Table 1) shows that the mean car cabin temperature (41.797°C) exceeds the mean air temperature (37.350°C) but is lower than the mean car skin temperature (47.390). This occurred even though all cars were parked under shaded conditions. The car parked under a tree shade registered a cabin temperature of 50°C (nine units higher than the average cabin temperature of the sample cars). Because all cars used in the experiment were white, the impact of car color on cabin temperature could be ignored. The highest variation in temperature was observed in the car skin temperature (SD = 5.4206).

3.1 Car cabin temperature

Linear regression modeling assumptions were tested to model car cabin temperature as a dependent variable and air temperature and car skin temperature as predictors. Table 3 shows the correlations among the variables of interest. The correlation between air temperature and car skin temperature was 0.02 and was not significant. To alleviate multicollinearity concerns, the correlations between independent variables (air temperature and car skin temperature in this case) should not exceed 0.7 (Gregorich et al., 2021). Thus, multicollinearity is not a concern here. Another desirable condition is the correlation value between predictor variables and outcome variables should exceed 0.3 (Ratner, 2009). Table 3 shows that the correlation values between cabin temperature and air temperature and car-skin temperature were 0.7 and 0.405, respectively. These correlation values are desirable.

TABLE 2 Passenger experience under varying cabin thermal conditions.

Case No	H_c	T_c	C_c	Body fatigue	Eye fatigue	Body heat	Skin dryness
1	40.0	35.0	1998.0	3	4	4	5
2	35.2	40.0	1,207.2	4	2	4	5
3	46.2	38.6	2828.1	4	2	4	1
4	39.8	39.4	2440.6	3	2	3	4
5	45.2	41.4	1,580.2	5	3	3	5
6	39.5	43.0	3,718.8	5	5	5	5
7	37.7	41.8	2347.1	5	5	5	5
8	29.6	49.9	2350.1	5	5	5	5
9	28.0	49.7	2117.1	5	5	5	3
10	30.3	38.7	1795.9	3	1	2	2
Averages	37.2	41.8	2238.3	4.2	3.4	4.0	4.0
11	24.0	32.0	2283.0	2	2	3	4
12	29.0	39.6	2725.0	3	1	3	4
13	34.3	36.6	3,908.0	3	1	3	1
14	23.3	37.4	2610.0	1	1	2	3
15	23.7	39.1	2950.7	3	1	2	3
16	24.9	42.5	3,334.5	3	3	4	4
17	25.7	40.5	2900.0	3	3	4	4
18	16.9	49.4	2624.4	4	4	4	4
19	19.9	45.7	2159.6	4	3	3	1
20	20.6	37.1	2455.0	1	1	1	1
Average	24.2	40.0	2795.0	2.7	2.0	2.9	2.9

TABLE 3 Correlations between car cabin temperature, air temperature, and car-skin temperature.

Correlations

		T_c	T_a	T_s
Pearson Correlation	T_c	1.000	0.700	0.405
	T_a	0.700	1.000	0.020
	T_s	0.405	0.020	1.000
Sig. (1-tailed)	T_c	.	0.012	0.123
	T_a	0.012	.	0.478
	T_s	0.123	0.478	.
N	T_c	10	10	10
	T_a	10	10	10
	T_s	10	10	10

The normal probability–probability (P-P) plot shows that the points follow a linear trend (Figure 2). Although the points deviate from the line slightly in the middle, overall, they follow a linear line, which is satisfactory. The scatterplot (Figure 2) shows point distribution as none exceeds +3 or −3 units (standard deviation) along either axis. This compactness may be attributed to the small sample size used in this study. For studies involving larger sample sizes, outliers are usually observed. Such points (outliers) may be removed from the analysis. Further discussion in this regard is beyond the scope of this article and interested readers might want to refer to the relevant literature (Terrin et al., 2005; Sarikaya and Gleicher, 2018).

Other parameters measured to test modeling assumptions included standard residual and Cook's distance (Table 4). The standard residual values ranged from −0.971 to 1.397 which is well within the threshold limit (±3). Likewise, the average Cook's Distances was 0.226; well below the threshold of 1.0 which shows

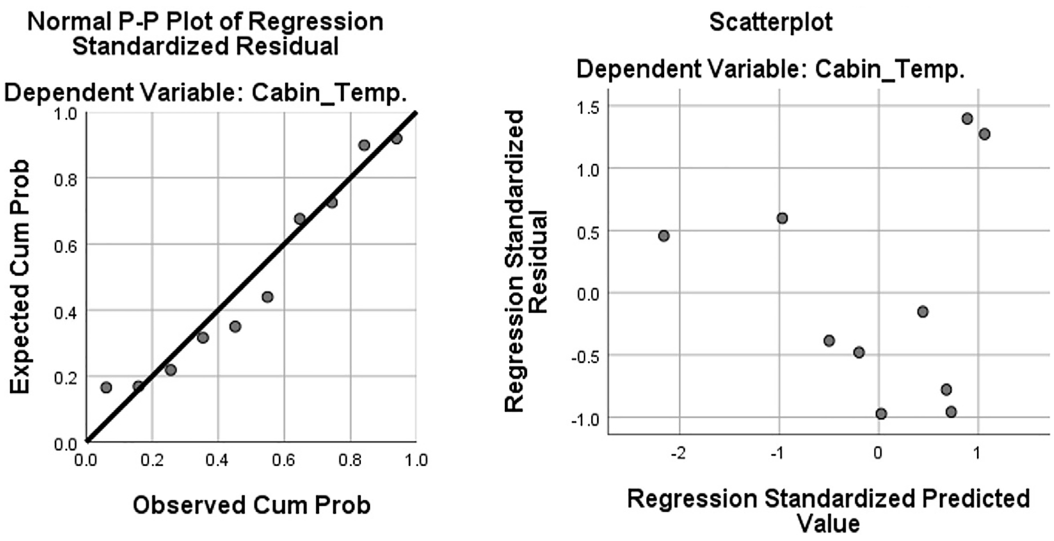

FIGURE 2
Normal P-P plot (left) and scatterplot (right).

TABLE 4 Residual statistics.

Residuals statistics

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	33.521	45.870	41.797	3.8314	10
Std. Predicted Value	-2.160	1.063	0.000	1.000	10
Standard Error of Predicted Value	1.146	2.672	1.715	0.484	10
Adjusted Predicted Value	30.383	46.304	41.850	4.8639	10
Residual	-3.1489	4.5271	0.0000	2.8587	10
Std. Residual	-0.971	1.397	0.000	0.882	10
Stud. Residual	-1.505	1.582	-0.008	1.079	10
Deleted Residual	-7.5610	5.8052	-0.0527	4.4862	10
Stud. Deleted Residual	-1.695	1.826	0.015	1.167	10
Mahal. Distance	0.225	5.217	1.800	1.635	10
Cook's Distance	0.001	1.058	0.226	0.324	10
Centered Leverage Value	0.025	0.580	0.200	0.182	10

a. Dependent VariableT_C.

that overall, data points do not exhibit peculiarities. However, the maximum Cook's distance was 1.058 indicating the presence of at least one outlier (an influential term that can lead to a regression model presenting a distorted image). Identifying such influential terms requires finding the Cook's distance value of the individual data points. Removing the outliers from the data set requires finding the impact of such removal on the least square estimates. Such detailed analysis might not be warranted for exploratory studies such as this one wherein the data points showed a reasonably low average value (of Cook's distance). Studies featuring large sample sizes and aiming to establish the relationships, however, need to analyze the possibility of removing of outliers from the data points. For more insights into this topic, interested readers should refer to Cook (1977).

The R-Square value for the model was 0.642, indicating that the predictor variables could predict 64% of the variation in the

TABLE 5 Model summary, ANOVA, and coefficients of cabin temperature.

Model summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	0.801a	0.642	0.540	3.2414	0.642	6.287	2	7	0.027

ANOVA[a]

Model		Sum of Squares	Df	Mean Square	F	Sig
1	132.119	2	66.059	6.287	6.287	0.027b
	73.549	7	10.507	10.507		
	205.668	9				

COEFFICIENTS AND COLLINEARITY[a]

Model		Unstandardized Coefficients		Standardized Coefficients	T	Sig	Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	-9.715	14.766		-0.658	0.532					
	Ta	0.942	0.308	0.692	3.060	0.018	0.700	0.756	0.692	1.000	1.000
	Ts	0.345	0.199	0.391	1.730	0.127	0.405	0.547	0.391	1.000	1.000

a. Dependent Variable: Tc b. Predictors: Ta Ts

dependent variable (Table 5). However, given the small sample size in this study, adopting a conservative estimate of the R Square value (adjusted R-Square) seems reasonable. The adjusted R Square value of the model is 0.54. Usually, R-Square values of more than 0.3 indicate acceptable regression models. The analysis of variance (ANOVA) showed that the regression model was significant at a 95% confidence level i.e., the *p*-value was less than 0.05. More specific measures of multicollinearity include tolerance and variance inflation factors (VIF) (Miles, 2014). The tolerance describes how much variability of a predictor variable is not explained by other independent variables in the model. The desired value of *tolerance* should exceed 0.1. Likewise, the desired value of VIF should be below 3, though some scholars (O'brien, 2007) permit higher VIF values. Table 5 shows that the tolerance and VIF value for both predictor variables is one, satisfying multicollinearity assumptions.

The air temperature variable has a standardized coefficient of 0.692 as compared to car skin temperature of 0.391, implying that more (nearly twice) variation in the outcome variable is explained by air temperature than car skin temperature. Notably, standardized coefficients offer a better comparison between the predicting power of independent variables compared to unstandardized coefficients. The unstandardized values of air temperature (0.942) and car skin temperature (0.345) are important from a modeling perspective. Thus, the car cabin thermal environment prediction model takes the following form based on the results of this study. Note that the air temperature is a significant predictor of the car cabin temperature ($p < 0.05$), but the car skin temperature is not ($p > 0.05$).

$$Car\,Cabin\,Temperature = 0.942^{*}\left(Air\,Temperature\right) + 0.345^{*}\left(Car\,Skin\,Temperature\right) - 9.715 \quad (1)$$

3.2 Passenger comfort evaluation

The impacts of cabin humidity, cabin temperature, and C O 2 concentration on the participants' perception of body heat, body fatigue, eye fatigue, and skin dryness were measured (Table 2). The participants rated their experience under 20 varying conditions. Since the driver engagement was brief (15 min) and there were distinct boundary conditions and respondents for every car, it was deemed necessary to validate that the recorded measurements would adequately

TABLE 6 Cronbach's alpha: Item-total statistics.

Item-total statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
Body Fatigue	9.60	13.305	0.720	0.633	0.835
Eye Fatigue	10.35	10.661	0.836	0.769	0.783
Body Heat	9.60	12.884	0.865	0.797	0.789
Skin Dryness	9.60	13.200	0.536	0.327	0.913

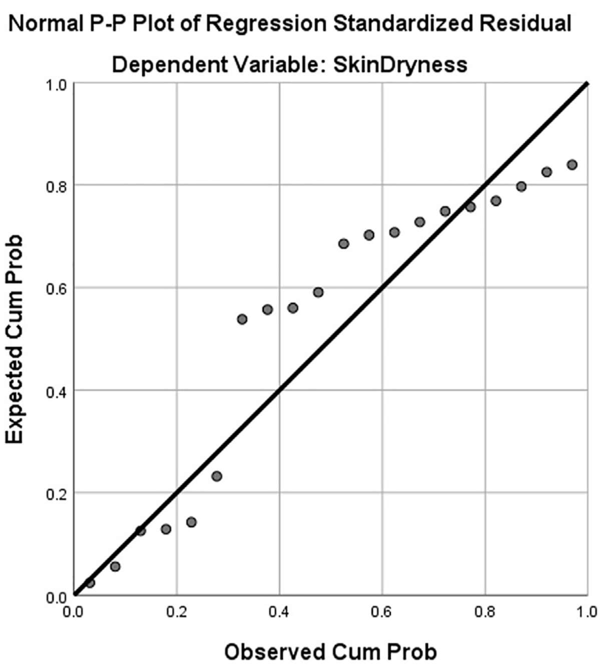

FIGURE 3
Normal P-P plot.

describe driver comfort levels. To this end, the internal consistency of the driver comfort data was measured using Cronbach's α. A minimum α value of 0.7 is required to ensure internal consistency (Tavakol and Dennick, 2011). The α value for driver comfort data turned out to be 0.880 showing high internal consistency. To improve the validation, the analysis of the sensitivity of α value to the scale items was performed (Table 6). The analysis showed that the responses on skin dryness were not consistent, as α jumped to 0.913 upon removing *skin dryness* from driver comfort data. Therefore, skin dryness was excluded from subsequent regression modeling in this study. The statistical significance of the relationships was also tested. Thus, the overall reliability of the research method was ensured.

To find if the skin dryness variable could be modeled using this data, a normal P-P plot of regression standardized residuals was plotted (Figure 3). The skin dryness rating data points did not satisfy the normality assumption. A non-linear regression or nonparametric statistical analysis was also unlikely to yield meaningful results because of the internal inconsistency of the measurement scale for skin dryness. Therefore, skin dryness was excluded from further analysis.

3.2.1 Perceived eye fatigue

Perceived eye fatigue was modeled as a function of H_c, T_c, and C_c levels. The correlations among predictor variables were less than 0.7, alleviating multicollinearity concerns. The correlation between cabin temperature and eye fatigue exceeded 0.3 indicating that temperature is a good predictor of eye fatigue. Humidity and CO_2 show insignificant weak correlations (<0.3) with eye fatigue. Diagnostic plots revealed that the assumptions of normality and homoscedasticity were satisfied (Figure 4). Other assumptions of linear regression including independence and linearity, were also satisfied but were not discussed here considering the exploratory nature of the study and for the sake of brevity. Interested readers are referred to the relevant literature (James et al., 2021) for further diagnostics of the data used in the study (Table 2).

The R-Square value for the model was 0.529, implying that the independent variables could predict a 52.9% variation in the dependent variable (Table 7). However, given the small sample size ($n = 20$), adopting a more conservative estimate of the R Square value (adjusted R Square) seems reasonable here. The adjusted R Square value for the model was 0.441 which is acceptable. The ANOVA results showed that the regression model was significant at a 95% confidence level i.e., the p-value is less than 0.05. The standardized coefficients of humidity,

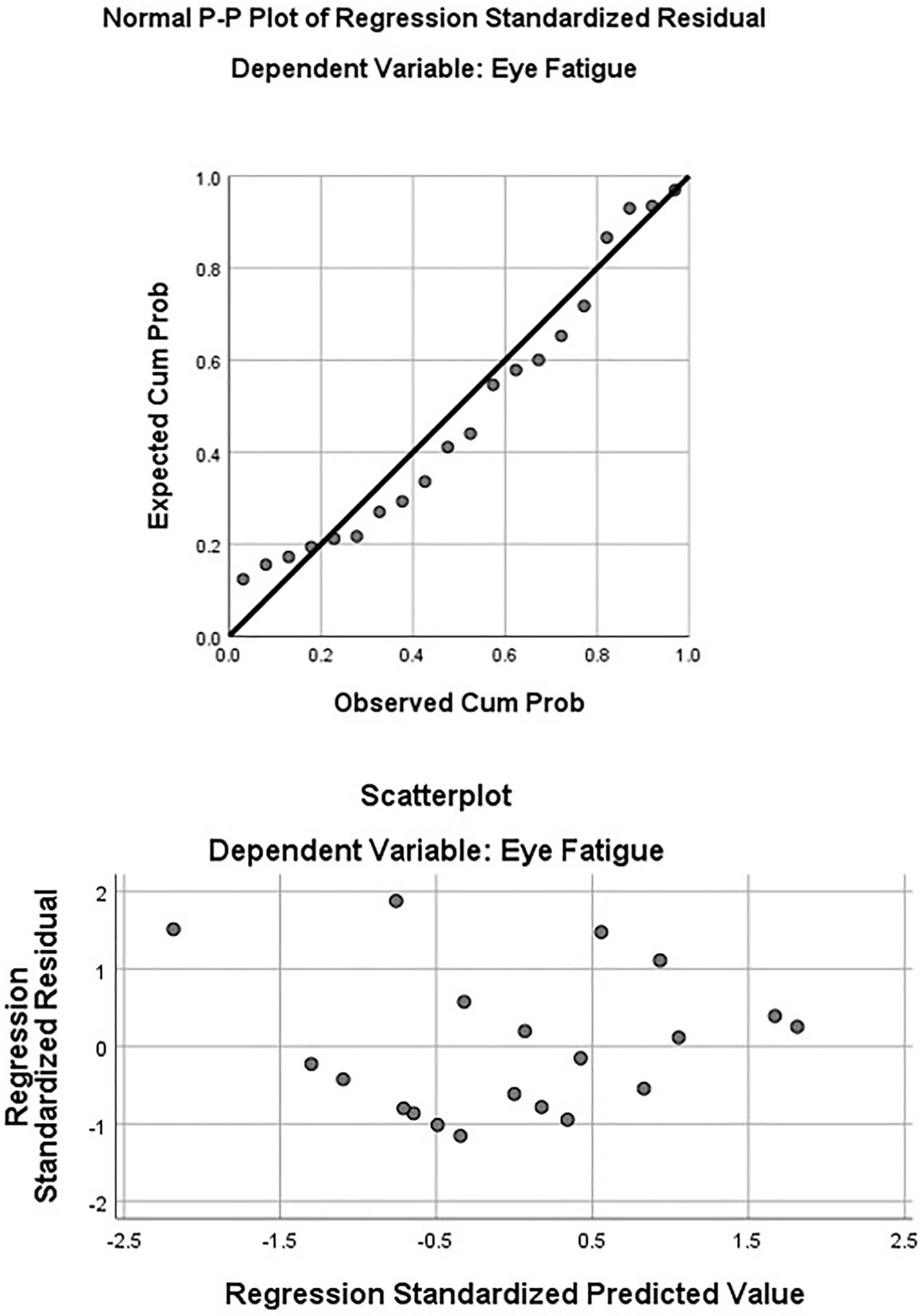

FIGURE 4
Diagnostic plots; eye fatigue.

TABLE 7 Model summary, ANOVA, and coefficients of eye fatigue.

Model summaryb

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	0.728a	0.529	0.441	1.140	0.529	6.000	3	16	0.006

ANOVA[a]

Model		Sum of Squares	Df	Mean Square	F	Sig
1	Regression	23.401	3	7.800	6.000	0.006b
	Residual	20.799	16	1.300		
	Total	44.200	19			

COEFFICIENTS[A]

Model		Unstandardized Coefficients		Standardized Coefficients	T	Sig	Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	-8.506	2.924		-2.909	0.010					
	HC	0.057	0.031	0.321	1.821	0.087	0.173	0.414	0.312	0.948	1.055
	TC	0.229	0.056	0.723	4.117	0.001	0.657	0.717	0.706	0.955	1.047
	CC	4.334E-5	0.000	0.019	0.109	0.915	-0.045	0.027	0.019	0.986	1.014

a. Dependent Variable: Eye_Fatigue b. Predictors: (Constant), CO2, TC, HC

temperature, and CO_2 were 0.321, 0.723, and 0.019, respectively, showing that cabin temperature explains more than twice the variation in eye fatigue as compared to cabin humidity. CO_2 levels explained little to no variance in the outcome variable. Cabin temperature is a significant explanatory variable ($p < 0.05$), but humidity and CO_2 levels were not. The collinearity statistics were satisfactory (tolerance >0.3 and VIF<3). Overall, the eye fatigue prediction model takes the following form.

$$Eye\,Fatigue = 0.57^{*}(H_C) + 0.229^{*}(T_C) - 8.506 \quad (2)$$

Because the impact of CO_2 concentration was negligible (to the order of 10^{-5}), it was excluded from the final model.

3.2.2 Body fatigue

Like eye fatigue, body fatigue was modeled as a function of H_c, T_c, and C_c levels. The correlation between body fatigue with predictors was more than 0.3 in the case of H_c and T_c and less in the case of C_c (Table 8). It implies that CO_2 level might not be a strong predictor of body fatigue. The correlation of body fatigue is highest for T_c (0.680), as shown in Table 8. Notably, the correlations among predictor variables were less than 0.7, reducing the multicollinearity concerns. Diagnostic plots showed that the assumptions of normality and homoscedasticity were not violated (Figure 5).

The adjusted-R Square value of the model was 0.787 which was significantly powerful, especially considering the small sample size (Table 8). Thus, the model could explain 78.7% of the variance of the body fatigue variable. The analysis of variance (ANOVA) showed that the regression model was significant at a 95% confidence level. The standardized coefficients of H_c and T_c were 0.606 and 0.801, respectively. It implied that the latter can explain 25% more variations in body fatigue than the former. On the other hand, the C_c level explained little to no variance in body fatigue (standardized coefficient = −0.035). T_c and H_c were statistically significant ($p < 0.05$), but C_c was not. The collinearity statistics are satisfactory (tolerance >0.3 and

TABLE 8 Model summary, ANOVA, and coefficients of body fatigue.

Model summaryb

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	0.906a	0.821	0.787	0.570	0.821	24.394	3	16	0.000

ANOVA[a]

Model		Sum of Squares	Df	Mean Square	F	Sig
1	Regression	23.756	3	7.919	24.394	0.000b
	Residual	5.194	16	0.325		
	Total	28.950	19			

COEFFICIENTS[A]

Model		Unstandardized Coefficients		Standardized Coefficients	T	Sig	Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	-7.439	1.461		-5.091	0.000					
	HC	0.087	0.016	0.606	5.570	0.000	0.447	0.812	0.590	0.948	1.055
	TC	0.205	0.028	0.801	7.392	0.000	0.680	0.879	0.783	0.955	1.047
	CC	-6.600E-5	0.000	-0.035	-0.332	0.744	-0.130	-0.083	-0.035	0.986	1.014

a. Dependent Variable: Body_Fatigue

VIF<3). Overall, the body fatigue prediction model is written as follows:

$$Body\ Fatigue = 0.087^{*}(H_C) + 0.205^{*}(T_C) - 7.439 \quad (3)$$

Note that the impact of CO_2 concentration on body fatigue was negligible (to the order of 10^{-5}) and was thus excluded from the final model.

3.2.3 Body heat

Like body fatigue and eye fatigue, body heat was also modeled using H_c, T_c, and C_c as predictor variables. Table 9 showed that the correlation between body heat and T_c was the highest (0.551) was statistically significant ($p < 0.05$). The intercorrelations among predictor variables were less than 0.7, thereby reducing the multicollinearity concerns. The correlations of T_c and H_c with body heat are more than 0.3 indicating that these predictors were good candidates for the intended regression modeling. C_c, on the other hand, showed insignificant ($p > 0.05$) and weak (<0.3) correlations with the body heat rendering its candidacy as a predictor variable, questionable. Diagnostic plots showed that the assumptions of normality and homoscedasticity were valid (Figure 6).

Given the small sample size, adopting the adjusted R Square value seemed reasonable, which was 0.451 (Table 9). Thus, the model can explain 45.1% of the variance in Body Heat. The ANOVA results showed that the regression model was significant at a 95% confidence level i.e., the *p*-value was less than 0.05. The standardized coefficients of humidity, temperature, and CO_2 were 0.487, 0.656, and 0.149, showing that the cabin temperature explained the most variation in body heat. However, the CO_2 level explained little to no variance in the outcome variable. Both T_c and H_c were significant explanatory variables ($p < 0.05$), but the C_c Level was not. The collinearity statistics were also satisfactory (tolerance >0.3 and VIF < 3). Overall, the body heat prediction model takes the following form based on the results of this study.

$$Body\ Heat = 0.065^{*}(H_C) + 0.156^{*}(T_C) - 5.565 \quad (4)$$

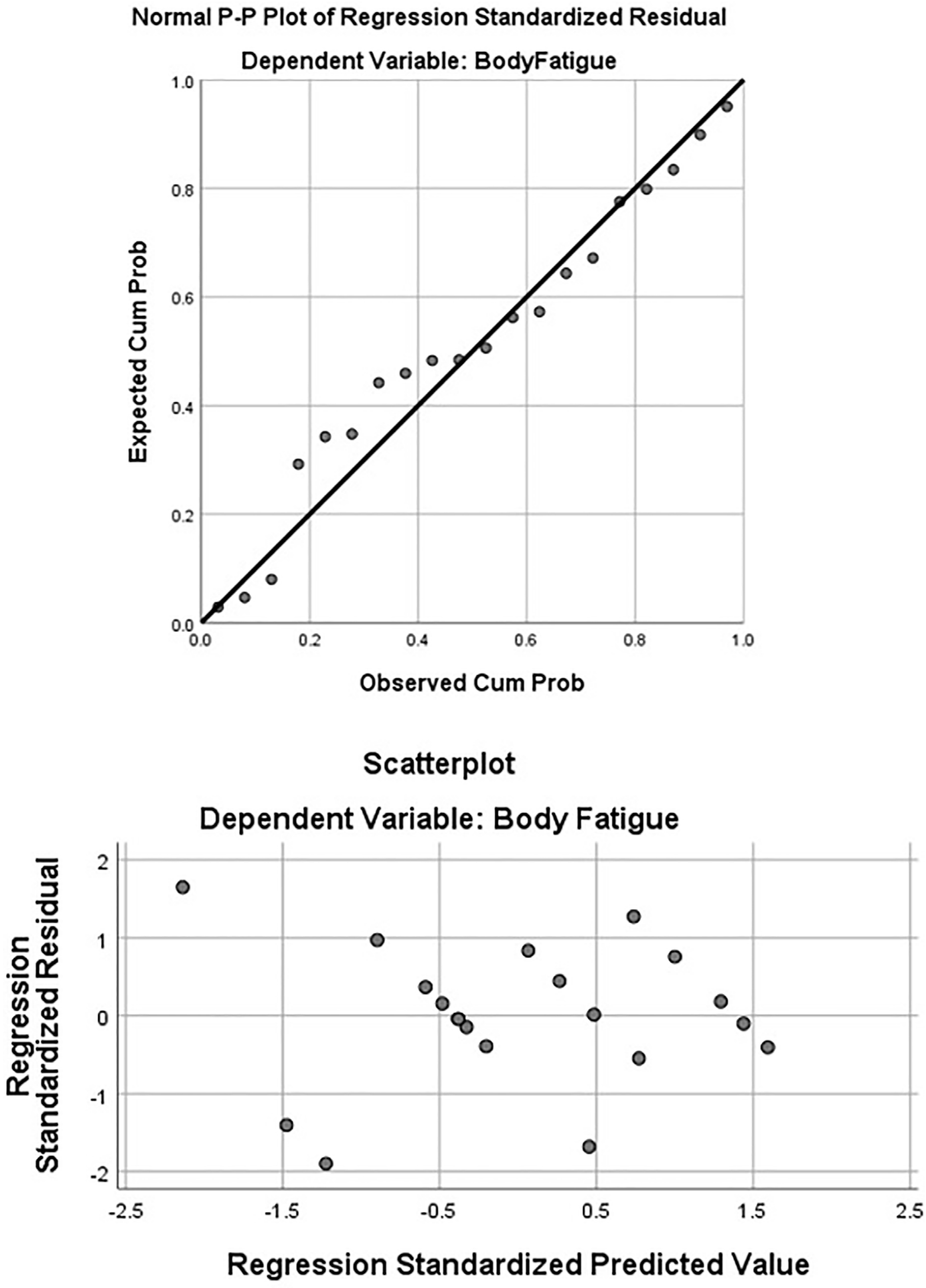

FIGURE 5
Diagnostic plots, body fatigue.

TABLE 9 Model summary, ANOVA, and coefficients of body heat.

Model summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	0.733a	0.538	0.451	0.849	0.538	6.206	3	16	0.005

ANOVA[a]

Model		Sum of Squares	Df	Mean Square	F	Sig
1	Regression	13.418	3	4.473	6.206	0.005b
	Residual	11.532	16	0.721		
	Total	24.950	19			

COEFFICIENTS[A]

Model		Unstandardized Coefficients		Standardized Coefficients	T	Sig	Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	-5.565	2.177		-2.556	0.021					
	HC	0.065	0.023	0.487	2.791	0.013	0.341	0.572	0.474	0.948	1.055
	TC	0.156	0.041	0.656	3.771	0.002	0.551	0.686	0.641	0.955	1.047
	CC	0.000	0.000	0.149	0.869	0.398	0.072	0.212	0.148	0.986	1.014

a. Dependent Variable: Body_Heat

Note that the impact of CO_2 concentration on body heat was not observed.

4 Discussions

The car cabin environment can be described in terms of thermal and air exchange parameters. The thermal factors used in this study were temperature and humidity and the air exchange factor was CO_2, which is consistent with the literature (Szczurek and Maciejewska, 2016). Intuitively, cabin temperature and humidity can be associated with the surrounding air temperature and humidity. However, simultaneously modeling air temperature and humidity as predictors can be misleading in that the two are strongly correlated, raising multicollinearity concerns. In this study, the correlation between air humidity and the air temperature was found to be perfect (0.995). This is why the cabin environment was studied only as a function of air temperature and not air humidity.

The driver perception of comfort data measured using a five-point Likert scale in this study is ordinal scale data (or at best interval scale data). Still, during the analysis, it is treated as ratio scale data which is a higher-level data type than the ordinal and interval scales. Future studies should treat such data carefully. Before using the data for parametrical statistical analysis, the assumptions of normality, linearity, homoscedasticity, and independence should be tested using diagnostic plots. If any of these assumptions do not hold, scholars should be careful in their choice of analysis methodology. Alternate analysis techniques are available for data that do not follow a normal distribution. For more discussion on this topic, interested readers are referred to the relevant literature on nonparametric statistical techniques (Kraska-MIller, 2013).

The correlation between cabin temperature and the surrounding air temperature was found to be strong (0.7) and significant ($p < 0.05$). However, the correlation between car skin temperature and car cabin temperature was weak (0.02). This may be attributed to several factors including shading conditions

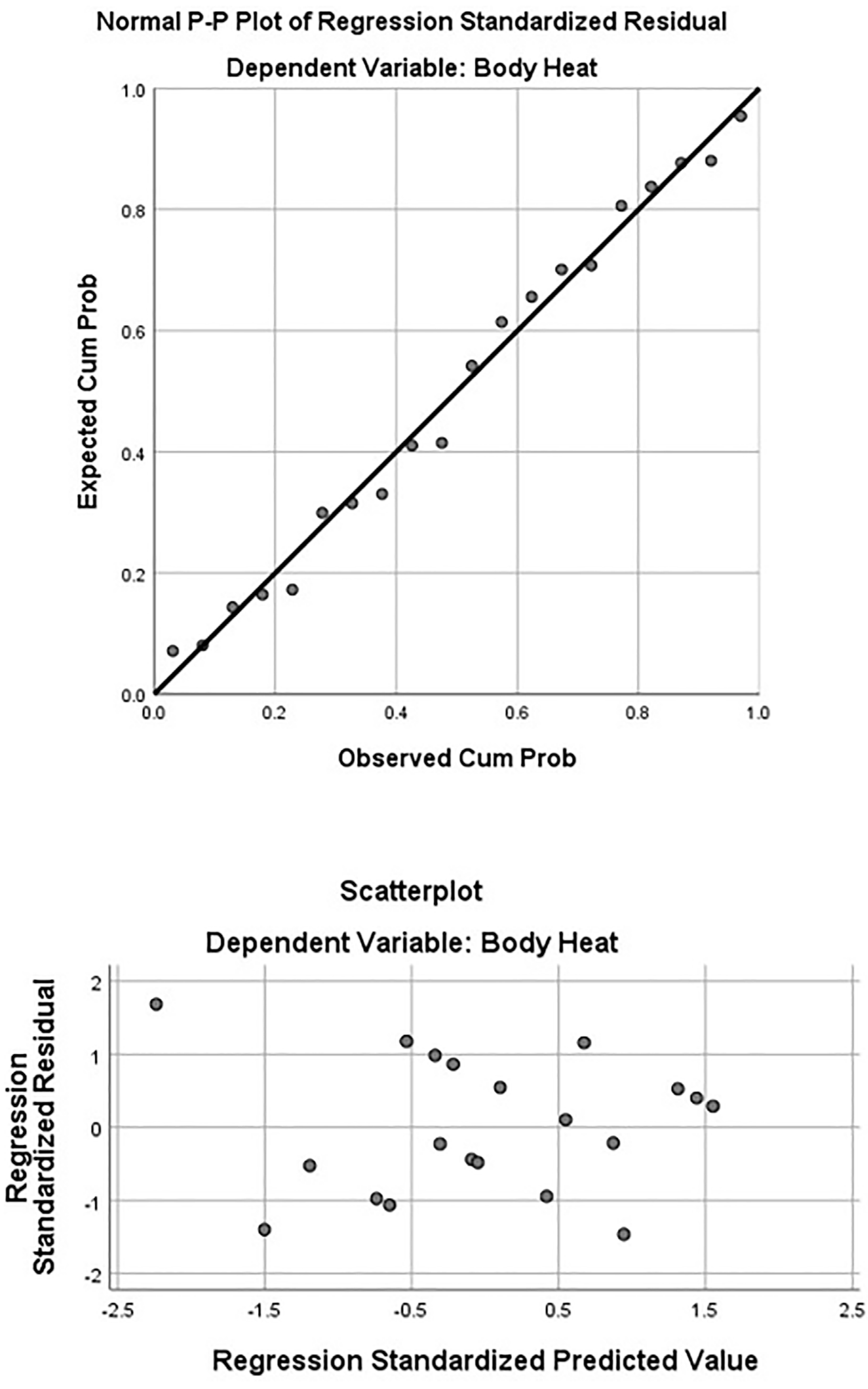

FIGURE 6
Diagnostic plots, body heat.

and the car skin temperature measurement technique used in this study which targeted maximum skin temperature instead of the average skin temperature. Still, this finding warrants further investigation with a larger sample size. In the final regression model, the air temperature explained three times the variation in the car cabin temperature as compared to the car skin temperature. Thus, air temperature is a better predictor of the car cabin thermal environment than car skin temperature.

Passenger comfort was measured using three constructs: body heat, body fatigue, and eye fatigue. The attempt to evaluate the fourth construct (skin dryness) was not successful as the internal consistency of data was low and diagnostic plots showed skin dryness data did not follow a normal distribution. The impact of cabin temperature on eye fatigue was estimated to be 2.25 times more than the impact of humidity (Table 7). An increase in temperature and humidity translated into an increase in eye fatigue. Eyeblink suppression and ocular surface irritation are known sources of eye fatigue for drivers (Sullivan, 2008). While more studies are needed to specify the repercussions of visual fatigue on driving tasks, an already-known characteristic of eye fatigue is that it has no permanent effect and can be resolved by taking rest (Megaw, 1995). The amount of rest needed to recover from visual fatigue is unknown (Sullivan, 2008).

The participants also reported an increase in body fatigue at high cabin temperatures and high humidity levels. The impact of cabin temperature on body fatigue was 132% more than that of cabin humidity. Likewise, for body heat, the temperature impact was 134% more than the humidity effect. However, the impact of CO_2 concentration on driver comfort (body fatigue, body heat, and eye fatigue) was negligible. This may be due to short-term exposure to the gas at low concentrations. The maximum level of CO_2 reached during the experiment was 3,908 ppm (Table 2). Future studies might consider assessing the impact of higher concentrations of CO_2 on driver fatigue.

One of the elements of novelty in this study is the use of real field settings to elicit drivers' perceptions of comfort levels concerning the changing cabin thermal profile. Previous studies used lab-based design to evaluate the dynamics of the car cabin environment and related driver experience (Tsutsumi et al., 2007; Mathur, 2016). Moreover, the literature does not offer any study on the impact of cabin heat on the driver comfort level in the UAE, given that the country features one of the hottest summers in the world. Driver experience in everyday situations is a product of both the external (air) and the internal (cabin) thermal profiles which differ from the lab-based experimental where the study participants usually sit in an AC environment before entering the climate chambers for the experiment. Hence, this study is expected to evoke a more lifelike thermal experience among drivers and to gather more realistic data on their comfort levels than the previous studies.

Another contribution of this study is the use of simple instruments only a thermal camera and an air quality measuring device is used for the cabin environment modeling. Another remarkable feature is the brief engagement time for the study participants (around 15 min including 10 min of sitting in the car and 5 min of filling out the questionnaire). Fewer equipment needs and shorter study duration mean that more stakeholders can use this method to study the cabin environment and driver comfort. Moreover, a psychometric approach was employed to evaluate driver comfort, which was previously analyzed using elaborate experimental settings (Tsutsumi et al., 2007; Mathur, 2016). Besides health impacts, the cabin thermal environment affects fuel consumption (Mansour et al., 2018). Cabin heating issues are also linked with parking behavior (parking choice, duration, visiting hours, etc.). Therefore, this study is expected to attract a broad readership including transport and health policymakers, parking managers, and scholars.

This study's findings can be applied to the assessment of comfort conditions and the design of car cabins according to comfort requirements. Driver comfort improved significantly and quickly (within 5 minutes) as in cabin thermal parameters were enhanced. For example, the average body fatigue reduced from 4.2 to 2.7 when the average relative humidity was reduced from 37.2% to 24.2%, and the temperature from 41.8°C to 40.0°C (Table 2). This finding corroborates the literature that asserts a quicker response to thermal stress in car cabins (Danca et al., 2016). Likewise, eye fatigue and body heat were also reduced from 3.4 to 4.0 to 2.0 and 2.9, respectively. However, note that these improvements in thermal comfort parameters are relative, and not absolute i.e., the study does not quantify thermal comfort levels. Future studies might want to consider differentiating thermal comfort from discomfort to strengthen this study's findings toward improving the ergonomics of car cabin thermal environments.

The limited sample size is one one of this study's limitations, which may have diminished the statistical analysis power. This also resulted in the lack of data required for model validation. Therefore, as the title suggests, this study should be treated as an exploratory study to guide future research in this domain. Another limitation is the direct measurement of constructs (body heat, body fatigue, and eye fatigue). Using Likert scale to measure complex constructs can be misleading. This limitation was addressed by ensuring an acceptable level of internal consistency in the employed scale (Table 6). Finally, the time of day when the reading is taken might affect body fatigue, eye fatigue, and body heat. For example, for the body fatigue readings taken in the afternoon, study participants might already be tired due to daylong activity which could affect their item rating on the Liker scale. Future research should consider accounting for the impact of such covariates.

5 Conclusion

This exploratory study demonstrated that modeling the car cabin thermal environment as a function of external air temperature and car skin temperature is feasible. Air temperature has a more pronounced impact on the cabin environment than car skin temperature. The cabin environment affects driver comfort level which can be measured using four constructs: body heat, body fatigue, eye fatigue, and skin dryness.

The first three constructs might be measured psychometrically, but skin dryness might not be measured in the same way. Respondents could not describe their feelings of skin dryness in an internally consistent manner, that is, they could not employ the same scale to rate skin dryness. This finding has implications for future studies that measure skin dryness or other similar constructs. The level of comfort was shown to be more sensitive to cabin temperature than it is to the cabin humidity and CO_2 levels. The CO_2 concentration studied in this experiment was 3,908 ppm, and its impact on driver comfort was negligible. This corroborates with the literature which suggests no serious health impacts for CO_2 levels below 5,000 ppm (Prill, 2000).

Car cabin environment modeling should be studied more often, focusing on passenger comfort. Simple research methods can facilitate various stakeholders in expanding the scope of this research domain. In this regard, methods requiring minimal instrumentation could facilitate relevant policymakers and practitioners in collecting empirical data for their specific needs. Thermal camera-based technologies are anticipated to become more widespread in near future; thanks in part to the advancement in drone-based thermal images. Aerial thermal photographs can help scan fleets of vehicles in parking lots and urban traffic revealing a wealth of information that was previously unavailable to parking managers and policymakers.

This study used only white cars to rule out the impact of car color on the cabin environment. Future studies might consider using different colored cars to gain more insight into the impact of car surfaces on the cabin environment. Moreover, the study used a small sample size that did not allow for evaluating the impact of shading conditions on the cabin environment. Future studies should consider increasing the sample size, that is, including more cars in the experiment, and allowing parking enough cars under different shading conditions to study and compare the impact of various parking types on the cabin environment and driver comfort. These findings would partly explain the choice, timing, and duration of parking, and would interest parking managers and urban transport planners whose businesses are sensitive to the dynamics of parking behavior. A large sample size will also allow for the validation of study findings.

Psychometric approaches to analyze constructs related to passenger comfort should be preferred over the other, more complex methods requiring instrumentation. This study demonstrated that reliable data on passenger comfort can be obtained and analyzed using effective parametric statistical techniques. Future studies should also consider using nonparametric statistical techniques, such as ordinal regression, should the assumptions of normality, homoscedasticity, independence, or linearity fail to hold. This, however, should be performed only on internally consistent data. In this regard, Cronbach's alpha is a useful parameter. Clear explanations of study constructs to study participants may aid in improving data internal consistency. In this study, skin dryness could not be evaluated due to low internal consistency. Interested readers are referred to Tsutsumi et al. (2007) for alternative methods of measuring skin dryness.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

KA: designed the research study, purchase equipment, handle logistical arrangement for the car experiment, conducted car experiment and driver interview, contributed in the literature, data analysis, results, conclusion, review the overall manuscript. Eng. MR: contributed in the study design, literature, data analysis, results and discussion.

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Conflict of interest

Author MR was employed by The Urban Unit Private Limited.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Toward sustainable cities: Monitoring thermal environment for buildings and pedestrian space using drone-captured 3D thermal imaging

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UAE's average temperature has risen in recent years and is expected to rise more in the next 40 years, creating a massive heat island agglomeration. Therefore, the demand for energy saving and diversified personal thermal management requires innovative solutions combining advanced building materials and structural designs to provide personal thermal comfort during indoor and outdoor activities. However, due to the complexities of structural designs and their associated materials, analytical and numerical strategies are for revealing real-world scenarios are limited. Therefore, full-scale experiments are required for exploring and demonstrating dynamic scenarios under thermal stress. This study aimed to explore the feasibility of using drone along with various thermal image analysis software that enables thermal photogrammetric mapping for monitoring and classification of heat rates based on building components surveyed across the UAEU campus. Thermal aerial images were collected in March 2022 and analyzed using SPSS, Agisoft Metashape Professional, DJI Thermal Tool, and FLIR for two buildings, A and B, and pedestrian spaces across UAEU's main campus in shaded, unshaded, and green zones. Noramilty and Kruskal-Wallis H tests were applied to examine if there was a statistically significant variation in surface temperatures. The pedestrian space thermal analysis showed that the natural shaded grass surface has the most tolerable heat environment (mean rank = 7.6), while the unshaded sand surface has the most unfriendly thermal environment (mean rank = 52.0), with an 18°C difference in mean surface temperature. The study also revealed the temperature evolution process and its dependence on building materials and structural designs, providing first-hand research data based on building components for the UAE climate, setting the path for future research in the era of sustainability and urban development.

KEYWORDS

thermal environment, urban heat island, urban agglomeration, personal thermoregulation, sustainable buildings

1 Introduction

Cooling is one of the most critical challenges for human beings during scorching summer days, especially performing outdoor activities (Farooq and Zhang, 2021). Nowadays, air conditioners have been widely adopted to manage personal thermal regulation. However, its inevitable drawbacks are massive energy consumption and toxic cooling agents that are causing heat-trapping, global warming, and ozone depletion over time (Gaonkar et al., 2018; Valinejadshoubi et al., 2021). Moreover, they are unserviceable for outdoor people to unload their heat stress. Therefore, several innovative solutions and strategies have been implied for providing sustainable solutions of personal thermal management while performing indoor as well as outdoor activities by incorporating energy efficient and passive cooling techniques that involve innovative structural designs and advanced materials such as solar reflective paints (Li et al., 2021), radiative coating (Gao et al., 2021), personal thermal wears (Peng and Cui, 2020), and so forth.

Monitoring the thermal environment of buildings is critical for assessing the performance of existing structures and identifying cost-effective energy-saving solutions (Zhang and Li, 2020; Aguilar et al., 2022). Therefore, a lot of research has been conducted on monitoring the thermal environment impact on outdoor and indoor scenarios (Han et al., 2022; Li et al., 2022). For instance, Maroy et al. (2017) investigate the use of infrared thermography (IRT) to estimate the thermal performance of insulating glass units (IGUs) in Belgium. First, numerical simulations were used to perform a sensitivity analysis on the boundary conditions. Quantitative IR measurements were then carried out on several glass kinds in the lab and on-site. Their findings show that the exact estimation of thermal resistance is not possible with IRT; however, it can distinguish poor insulating IGUs from good and moderate ones, provided that the IRT inspection should be carried out under cloudy conditions and with a temperature difference of at least 15.0°C.

Similarly, Kumar et al. (2018) used outdoor observations to analyze the thermal performance of high thermal mass office spaces operating under natural ventilation mode for the climatic conditions of Jaipur, India. Part of the field measurement data is utilized to construct indoor-outdoor correlations, which are then validated against the rest of the data to predict indoor temperatures in high-density office buildings. Furthermore, when applied to predict indoor temperatures of similarly constructed passive structures, established correlations demonstrated an excellent correlation coefficient (R2 ≥ .92). The use of thermal mass in the building envelope can eliminate an extra 40% and 98% of total thermal discomfort time during the summer and winter seasons, respectively.

Zheng et al. (2020) evaluate the thermal performance of the building's entire envelope structure. They present a thermal infrared (TIR) external evaluation approach and devise a way to obtain TIR images of the building envelope using a UAV outfitted with an infrared camera and create a 3D point cloud model that includes temperature data for any specified locations. The created 3D TIR model has a temperature accuracy of 5.0°C, whereas 81.25% of the measuring spots have a temperature accuracy of 3.0°C, which is acceptable for the thermal infrared technique. As a result of this technology, a comprehensive, accurate, and efficient *in situ* evaluation of the building envelope in the urban environment is achievable.

In contrast to conducting an outdoor/field observation or on-site/lab experiment, Kirimtat and Krejcar (2018) gave a comprehensive overview of past studies investigating the anomalies of building envelopes using IRT. They categorized the applications by measuring methods, analysis schemes, and analysis types to demonstrate IRT's potential in building envelope inspection for providing energy-efficient solutions. According to key reviews and findings of their research, heat loss, moisture, and air leakage all have a substantial impact on the energy performance of building envelopes.

Heat loss through the building envelope can be divided into two categories: heat loss through the plain portions, measured by the thermal transmittance (U-value), and heat loss through thermal bridging O'Grady et al. (2017a). Several studies have evaluated the heat loss induced by thermal bridging using various methods (Heinrich and Dahlem, 2000; Zalewski et al., 2010; Ascione et al., 2013; Ascione et al., 2014). For instance, O'Grady et al. (2017a) used an outdoor infrared thermographic survey to estimate the thermal bridging performance and devised an efficient, non-destructive, *in situ* testing approach. They include an assessment of the wind velocity impact on the Ψ-value—linear thermal transmittance since wind velocity substantially impacts heat losses through the building envelope. The results revealed that the Ψ-value strongly depends on wind velocity, making it nearly impossible to compare measurements of the -value performed under different wind conditions. A strategy is suggested for converting the Ψ-value measured at any wind velocity to a standard value corresponding to a 4 m/s wind velocity. This modification approach makes the methodology generally applicable from a practical standpoint.

O'Grady et al. (2017b) also offered another quantitative ITT methodology for calculating structures' thermal bridge heat flow rate. The methodology can be used to calculate the Ψ-values of any existing building envelope. This innovative method used the ITT alone to determine the actual heat flow rate induced by thermal bridge qTB and -value, with no other supporting methods. The qTB and Ψ-value determined using the supplied approach accurately reflect the thermal bridge's actual thermal performance.

Recently, Leggiero et al. (2021) presented a comprehensive workflow for quantifying radiative heat loss from building envelopes. This includes the setup and technique for fast building accurate 3D thermographic models and analyzing them with software designed specifically for this purpose (VAMPIRE- a Versatile Analysis and Measurement Protocol for Infrared Emissions). Three analytical models for building envelope radiative heat loss are implemented and tested through controlled tests for viability. The workflow is then shown by assessing the thermal radiation losses of two buildings on the University of North Georgia's campuses. Their findings implied that the approach could promptly yield accurate radiative heat loss measurements and could be a valuable complement to more thorough thermal analysis techniques.

In addition to thermal monitoring of buildings, providing personal thermal management will perform outdoor activities necessitate the thermal environment monitoring of outdoor spaces, such as parking lots and pedestrian spaces. Nan et al. (2022) analyzed the difference in the thermal environment of eight different parking lots in Hangzhou, China, and proposed that the shading significantly influenced the management of thermoregulation; however, the cooling effect of trees was found the stronger than the artificial shading. Meanwhile, the grass is found to be helpful in mitigating urban heat agglomeration by decreasing the surface temperature (Nan et al., 2022). Yin et al. (2022) analyzed the thermal environment of outdoor public spaces. The authors concluded that the thermal comfort in outdoor spaces is highly influenced by the atmospheric conditions, leading from the highest temperatures in summer to freezing in winter. Therefore, careful consideration is required while selecting building and shading materials and structural orientations to ensure the thermal comfort of occupants during all seasons of the year (Yin et al., 2022).

The use of unmanned aircraft systems (UASs) has grown recently across a wide range of inspection applications (Falorca and Lanzinha, 2021; Alkaabi and El Fawair, 2022), and its infrared photography has proven to be more advanced than traditional auditing methods (Corsi, 2010). The infrared audit is an intriguing tool among the energy audit techniques and is widely adopted. The two most important elements in producing a top-notch infrared audit, in accordance with Dall'O et al. (2013), are high-performance equipment and the infrared auditor's technical expertise. They discussed the outcomes of an infrared audit campaign for 14 pre-existing buildings in Milan Province, Italy, erected throughout various eras and with varied building technologies. The thermal resistance obtained indirectly by thermography of the opaque walls of the structures under investigation were compared to real known values to verify the method's reliability and the margin of error. The study found that the implementation of this method is adequately trustworthy in solid-mass structure buildings, which are the most common in Italy; however, the percentage of variation is very high in buildings with insulated external walls.

Focusing on the application of UAS for energy audit purposes, Rakha and Gorodetsky (2018) provided a thorough overview of the literature on UAS applications in the built environment. They identified a standard protocol for using a UAS for energy audit missions, and their analysis highlighted current UAS-based thermal imaging techniques and methodology. As part of the findings for the literature study, investigative methodologies for before, during, and post-flight studies were designed, calibrated, and tested on the Syracuse University campus. As a move toward standardizing the automation of building envelope inspection, the findings recommend further empirical experimentation and research replication to improve procedure accuracy.

The average temperature in the UAE has risen by over 1.5°C in recent years mainly as a result of greenhouse gas emissions, and projections indicate that it could rise by another 2.5°C in the next 40 years, eventually generating a massive heat island agglomeration (Issa, 2016; Ksiksi and Al-Blooshi, 2019; Hill, 2021). Considering these challenges, sustainable cities and communities are a key goal among all SDGs under the local agenda of the UAE national government. This key sustainability objective necessitates a thoughtful exploration of how we build buildings and communities to be resilient, safe, and sustainable in a way that responds to future challenges such as climate change and the Emirati community's socio-economic growth. For Example, monitoring the surface temperatures of buildings is critical for assessing the performance of existing structures and identifying cost-effective energy-saving solutions. Therefore, this study explores the application of thermal imagery-based cameras on UAVs for mapping urban structures for the first time to the best of our knowledge for the climatic conditions of the UAE. The flight missions were conducted throughout the weekend of 26 and 27 March 2022, at the United Arab Emirates University (UAEU) main campus to examine the feasibility of employing UAVs for thermal photogrammetric mapping for assisting in the monitoring and classifying of heat rates based on orientation and building components, such as glass, cement, sand, etc., because the layout, orientation, materials, and on-site location directly influence the heat gain in the buildings. Buildings A and B were chosen for this study, with Building A having an E-shaped design surrounded by an artificial shaded pathway and open spaces. Building B is oval in shape, with a large artificial water pool on one side and open green space on the other. Furthermore, the spatial distribution of thermal comfort is evaluated and analyzed for selected pedestrian spaces and parking lots based on their structural configurations, such as shaded, unshaded, and areas near plants or trees. Overall, the findings are expected to be useful to decision-makers concerned with issues of sustainability and urban development, such as monitoring the effects of the urban thermal environment and developing corresponding mitigation strategies for building components and thermal environment in pedestrian spaces to ensure the personal thermal management of occupants with minimum footprints.

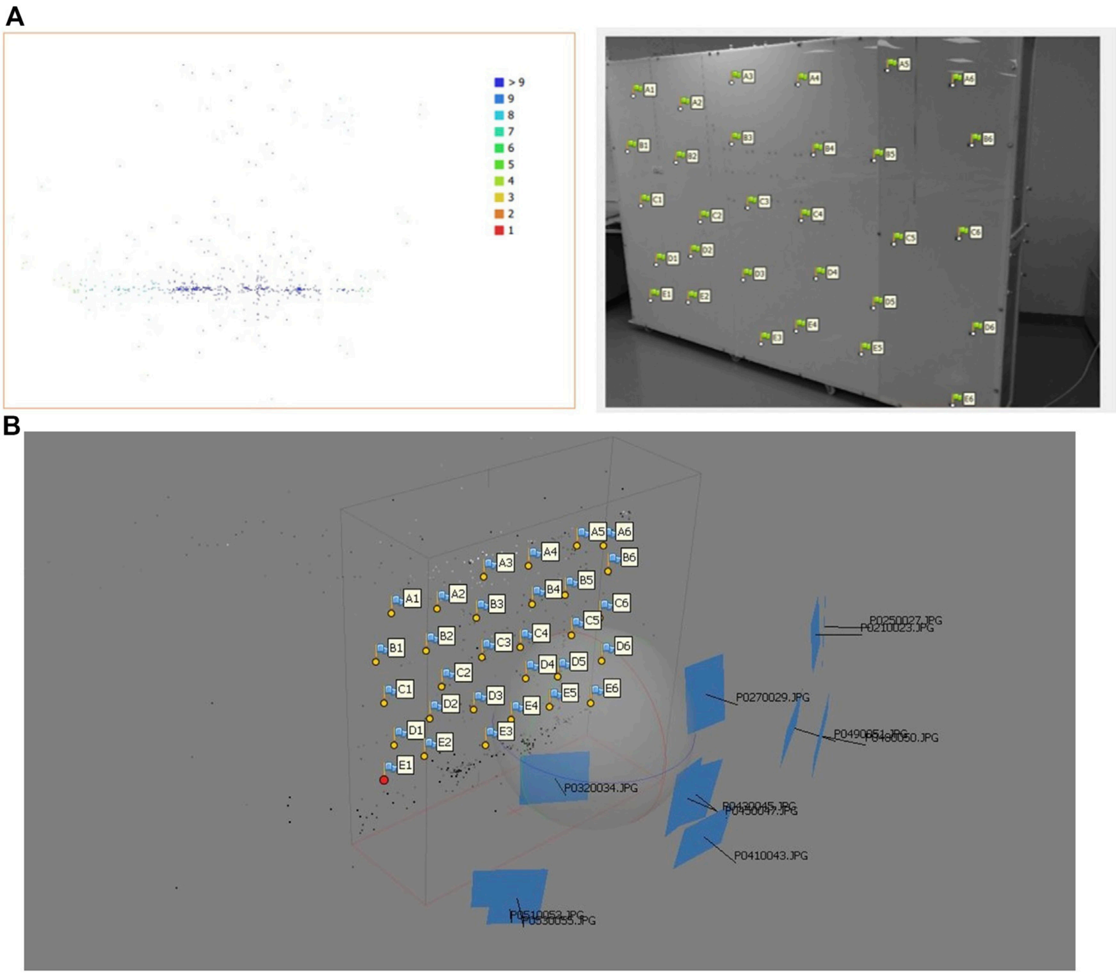

FIGURE 1
(A) Camera locations and image overlap using physical board in UAEU Laboratory; **(B)** Perspective view showing the location of exposure stations, camera orientation and GCPs using Agisoft software.

2 Research methodology

2.1 Parrot Anafi thermal camera calibration procedure

Firstly, the drone camera Parrot Anafi Thermal was calibrated, and the interior orientation parameters (IOP) were calculated to set and maintain the precision and accuracy of the drone. The camera calibration was conducted at the E5 Laboratory in the UAE University, and the camera's inner orientation parameters were also numerically measured, as shown in Figure 1A. The thermal camera has been calibrated according to the reflection temperature in each measurement with a corresponding temperature and relative humidity of 22.0°C and 42%, respectively. The reference standards, indication errors, and measurement uniformity are briefly explained in the Supplementary Tables SA1–SA3, respectively. In addition, the interior orientations of the camera were checked to confirm that they matched the principal distances (c) and principal point locations (xp, yp) as well as picture coordinate corrections for various deviations from the expected perspective geometry. The IOP was determined using a bundle adjustment with self-calibration.

The existing wide-format calibration field was used to calibrate the new drone camera. The Calibration process was conducted in accordance with the workflow shown in Figure 2. After applying the camera calibration steps, the error results were determined. The Parrot Anafi thermal camera was calibrated, and the drone was ready to be used for photogrammetric mapping. The perspective location of exposure stations, and camera orientation, are shown in Figure 1B using Agisoft software.

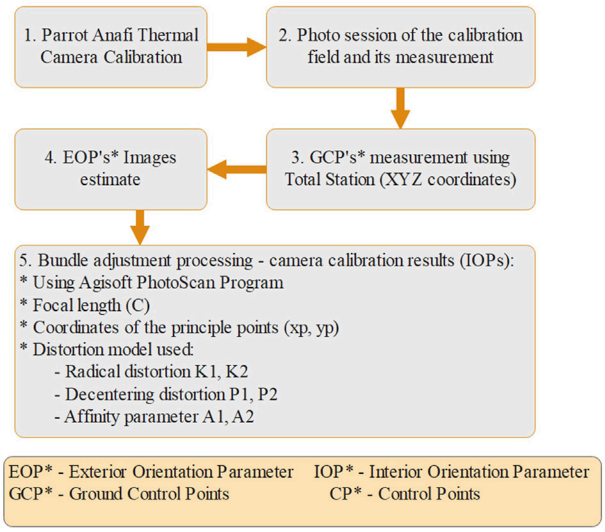

FIGURE 2
Camera calibration Workflow.

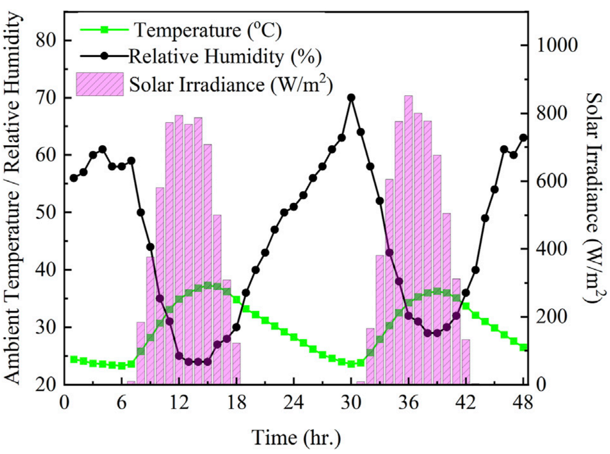

FIGURE 3
Metrological data for Al Ain (24.1302°N, 55.8023°E) on 26 March 2022 and 27 March 2022.

2.2 Fieldwork and drone mission planning

Maintaining the thermoregulation of students and workers while performing indoor and outdoor activities is essentially required to maximize work productivity. Therefore, to analyze the impact of the ambient temperature on the heat gain of building materials and shadings, the flight missions were conducted throughout the weekend of 26 and 27 March 2022, at the UAEU main campus. Due to summer break during the peak summer months, when students are not required to come, this time of the year was selected for conducting the experiments. In comparison, it is still the on-going spring semester during which the students are required to attend their classes on-campus, while the weather profile, as shown in Figure 3, shows that the peak daytime solar irradiance is high, with temperatures reaching up to 40.0°C and low relative humidity, making it essential to monitor the thermal environment. Furthermore, the flight missions were conducted during the weekend to reduce the influence of students' bodies detected by the thermal camera. Pix4Dcapture and Parrot FreeFlight 6 applications were employed to create autonomous drone flight plans and missions and take needed aerial image shots. Tables 1, 2 illustrate the main characteristics of the two drones utilized in this study and associated flight mission plans for capturing aerial images in both visible and thermal modes.

2.3 Thermal analysis and 3D energy modeling

Many thermal aerial images were taken by the drone for two different buildings, referred to as A building and B Building, as well as pedestrian spaces across the main campus of UAEU. Thermal analysis and 3D model development were carried out using the following software:

1- Agisoft Metashape Professional (1.8.0 build 13794): used for developing 3D models (Visible RGB, Thermal) taken by MATRICE 300 RTK
2- DJI Thermal Analysis Tools 2 (V21.18): used for thermal analysis for selected thermal images taken by MATRICE 300 RTK
3- DJI Thermal Analysis Tool (V1.1.0): used for thermal analysis for selected thermal images taken by MATRICE 300 RTK
4- FLIR: used for thermal analysis for selected thermal images taken by Parrot ANAFI Thermal drone

3 Imagery analysis

3.1 Development of a three-dimensional (3D) model for the A building—UAEU: RGB

Using Agisoft Metashape Professional Software, the aerial photos captured during the drone flight were calibrated, as well as the camera locations and error estimates, as shown in Figures 4A, B and Table 3. The software then processes the calibrated photos to create and construct a three-dimensional model of the A building and its associated digital elevation model using 1,474 aerial images, as shown in Figures 4C, D.

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TABLE 1 The characteristics of the drones and cameras employed in this research project.

Drone type	Characteristics
Drone 1: parrot ANAFI thermal	• Drone name: parrot ANAFI thermal (1.8.2)
	• Weight: 315 g
	• Max flight time: 26 min
	• Operating temperature: from −10°C to 40°C
	• Thermal-imaging camera: Sensor: FLIR lepton 3.5 microbolometer (radiometric) Sensor resolution: 160 × 120 HFOV: 57 Pixel pitch: 12 µm Spectral band: 8–14 µm Thermal sensitivity: <50 mK (.050°C) Photo resolution: 3264 × 2448 (4/3)
Drone 2: MATRICE 300 RTK	• Drone name: MATRICE 300 RTK
	• Max takeoff weight: 9 kg
	• Max flight time: 55 min
	• Operating temperature: −20°C to 50°C (−4°F to 122°F)
	• Hovering accuracy (P-mode with GPS): Vertical:
	±.1 m (vision system enabled)
	±.5 m (GPS enabled)
	±.1 m (RTK enabled) Horizontal:
	±.3 m (vision system enabled)
	±1.5 m (GPS enabled)
	±.1 m (RTK enabled)
Drone 2: vision system	• Obstacle sensing range: forward/backward/left/right: .7–40 m upward/downward: .6–30 m
	• FOV: forward/backward/downward: 65° (H), 50° (V)—left/right/upward: 75°(H), 60°(V)
	• Operating environment: surfaces with clear patterns and adequate lighting (>15 lux)
Drone 2: infrared ToF sensing system	• Obstacle sensing range: .1–8 m
	• FOV: 30° (±15°)
	• Operating environment: large, diffuse and reflective obstacles (reflectivity > 10%)
Drone 2: FPV camera	• Resolution: 960 p
	• FOV: 145°
	• Frame rate: 30 fps
Zenmuse H20 (camera)	• Radiometric thermal camera resolution: 640 × 512 px

TABLE 2 Flights Planning and aerial surveys.

Flight #	Drone type	Type of image	Date	Time	Area covered	Flight mission plan	Flight altitude	Image format
1	Parrot ANAFI Thermal	Thermal visible	26 March 2022	10:30 a.m.–11:00 a.m.	Pedestrian spaces	Manual	1.5 m	JPG
2	MATRICE 300 RTK	Thermal visible	27 March 2022	9:30 a.m.–12:00 p.m.	B (building exterior and interior)	Grid	50 m	JPG
3	MATRICE 300 RTK	Thermal visible	27 March 2022	12:30 p.m.–1:30 p.m.	A (building exterior)	Grid	50 m	JPG
4	MATRICE 300 RTK	Thermal visible	27 March 2022	1:00 p.m.–1:38 p.m.	Pedestrian spaces	Grid	50 m	JPG
5	MATRICE 300 RTK	Thermal visible	27 March 2022	1:40 p.m.–1:44 p.m.	Pedestrian spaces	Manual	3–5 m	JPG

3.2 Development of a thermal 3D for the A building—UAEU

Agisoft Metashape Professional Software was used to construct a thermal 3D model for the A building at UAEU campus using 737 thermal aerial images, as shown in Figures 4E, F; Table 3.

3.3 Thermal analysis for B building—UAEU

This study explores the temperature environment of the B building. The heat demand is determined by several factors, including:

- The insulating characteristics of the construction material are referred to as the U-values of the walls
- The amount of heat carried away by air movement varies according to the size of the building and the number of windows.
- The difference in temperature between the inside and outside of a building—the cooling energy required for cooling a building varies by season.
- Double glazed spandrel (DGS) glass is used in all strucures in this study to ensure the opaqueness along with the excellent strength.

Thermal assessments are crucial throughout the design phase of a building because they provide an estimate of the energy required to cool or heat the building. Figure 5 showcases the side views of the B outdoor building, with thermal images illustrating the difference in external temperatures using the DJI Thermal Analysis Tool. Thermal imaging measurements for the B indoor building are shown in Figure 6.

3.4 Thermal environment analysis in pedestrian spaces—UAEU

3.4.1 Case 1: Thermal environment in shaded pedestrian spaces around the teaching buildings

Figure 7 shows a comparison between the visible image and the infrared image analysis for the pedestrian zone (Case 1) using FLIR Tools. As indicated from spot measurements that shaded surface (Sp1: 30.2°C; Sp2: 30.9°C; Sp21: 31.1°C) tends to be cooler than an unshaded surface directly exposed to the Sun (Sp10: 46.3°C; Sp11: 45.1°C), with a substantial temperature difference of around 14.0°C–16.0°C. Therefore, pedestrian zones located between buildings and covered by shads tend to have a more tolerable heat environment than unshaded zones.

3.4.2 Case 2: Thermal environment in pedestrian area adjacent to open green spaces (garden a and b)

A comparison analysis of the thermal environment in pedestrian zones (a) and (b) adjacent to green spaces and tree shading show a tolerable heat surface environment using FLIR Tools, as shown in Figure 7. For example, shaded surfaces in Case 2-a located near trees tend to have lower temperatures (Sp1 30.2°C; Sp8 30.3°C; Sp9 31.1°C; Sp2 30.9°C) than exposed surfaces to the Sun directly (Sp4 47.1°C; Sp5 46.4°C) as indicated in Figure 7 Case 2-a. In Case 2-b, the shaded surfaces also tended to be tolerable for pedestrians (Sp7 30.9°C; Sp8 31.3°C; Sp10 31.0°C) (Figure 7).

3.4.3 Case 3: Thermal environment in pedestrian spaces around the campus parking area

Thermal analysis for different points around the campus parking lot reports higher temperature measurements using DJI Thermal Analysis Tool 2, as illustrated in Figure 7. The excessive temperatures (exceeding 40.0°C) were primarily attributed to the pavement's construction materials and lack of sufficient shade.

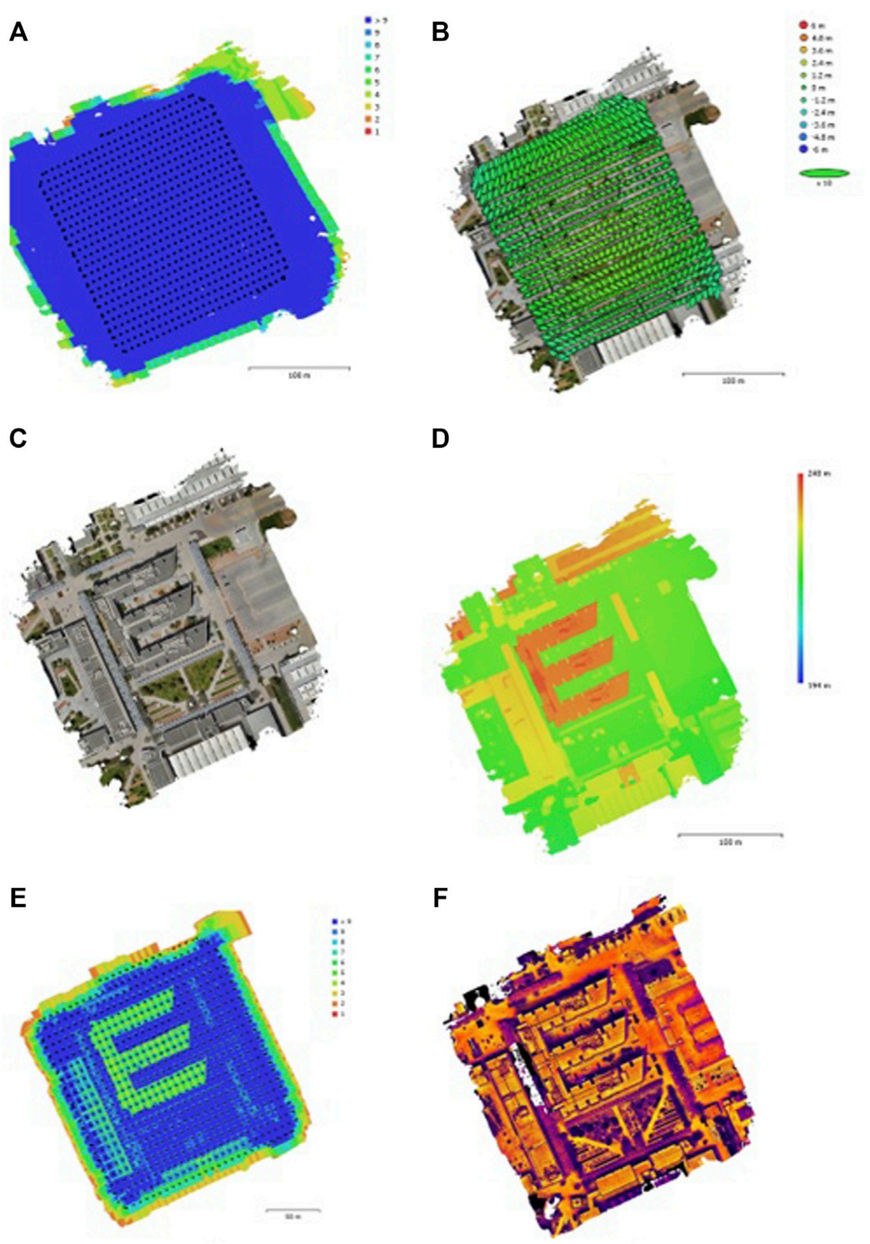

FIGURE 4
(A) Camera locations and image overlap; **(B)** Camera locations and error estimate*; **(C)** Constructed 3D model for A building; **(D)** Digital elevation model for A building using Agisoft Metashape; **(E)** Camera locations and image overlap; **(F)** Thermal 3D model for A building. * Note: Z error is represented by ellipse color. X, Y errors are represented by ellipse shape. Estimated camera locations are marked with a black dot.

4 Results

4.1 Analysis and interpretation

Statistical Package for the Social Sciences (SPSS) version 26 from IBM was used to analyze the collected data. First, a descriptive statistics test was conducted. Next, the normality distribution test for the data was performed using Shapiro-Wilk and Kolmogorov-Smirnov tests, which were assessed at the 5% significance level. In all cases, the *p*-value was less than (<) .05, which led to do a non-parametric test. The Kruskal-Wallis test was then used to analyze and contrast the statistical differences between the study's more than two independent groups. Afterward, Spearman's Rank Correlations was performed to examine the strength (weak, moderate, strong, etc.) and type (positive or negative) of the relationship between the overall

TABLE 3 A building 3D model (RGB, Thermal): Cameras' specifications and average camera location error.

A building 3D model (RGB)				
Number of images:	1,474	Camera stations:		1,473
Flying altitude:	45.5 m	Tie points:		1,133,590
Ground resolution:	9.92 mm/pix	Projections:		4,104,537
Coverage area:	.0629 km^2	Reprojection error:		1.38 pix
Camera model	**Resolution**	**Focal length**		**Pixel Size**
ZH20T (4.5 mm)	4056 × 3040	4.5 mm		1.6 × 1.6 µm
ZH20T (25.39 mm)	5184 × 3888	25.39 mm		1.45 × 1.45 µm
ZH20T (21.75 mm)	5184 × 3888	21.75 mm		1.45 × 1.45 µm
ZH20T (10.14 mm)	5184 × 3888	10.14 mm		1.44 × 1.44 µm
X error (cm)	**Y error (cm)**	**Z error (cm)**	**XY error (cm)**	**Total error (cm)**
52.6566	47.3454	64.2962	70.8118	95.6468
A building 3D model (thermal)				
Number of images:	737	Camera stations:		736
Flying altitude:	50 m	Tie points:		418,208
Ground resolution:	4.16 cm/pix	Projections:		1,458,208
Coverage area:	.0492 km^2	Reprojection error:		.315 pix
Camera model	**Resolution**	**Focal length**		**Pixel size**
ZH20T (13.5 mm)	640 × 512	13.5 mm		12.3 × 12.3 µm
X error (cm)	**Y error (cm)**	**Z error (cm)**	**XY error (cm)**	**Total error (cm)**
25.0284	27.8358	38.1515	37.4333	53.4489

Note: X, longitude; Y, latitude; Z, altitude.

temperatures of the three variables (B OBSSM[1], B IBCSM[2], and B ELFSM[3]) of the B building in the study.

4.2 Descriptive analysis

This study's descriptive statistics data comprised the thermal conditions of the following variables: Pedestrian Spaces Shaded Surface types (PSSST), the A outdoor building components and surface materials (A OBCSM), the B outdoor building sides and surface materials (B OBSSM), the B indoor building components and surface materials (B IBCSM), and the B external landscape features and surface materials (B ELFSM). For each variable, descriptive statistics (mean and standard deviation) were computed (Table 4). According to the descriptive statistics of mean values, the thermal environment in the A OBCSM was the most intense, followed by the PSSST and the B OBSSM. The descriptive statistics' mean values revealed that B ELFSM had the least intense thermal environment. However, the B IBCSM had the biggest sample size (N), the smallest standard error of the mean, and the least amount of variation (standard deviation). All the other variables had positively skewed distributions, except A outdoor building components and surface materials (A OBCSM). Also, A OBCSM recorded the highest maximum temperature (°C), while B ELFSM had the lowest minimum temperature (°C). B IBCSM and B ELFSM had the highest and lowest kurtosis values, respectively.

In accordance with the study's data, the PSSST variable consists of six groups, namely: 1) unshaded sand area (N = 11, 18.6%), 2) unshaded cement area (N = 15, 25.4%), 3) artificial shade cement area (N = 6, 10.2%), 4) natural shade cement zone (N = 11, 18.6%), 5) unshaded grass zone (N = 11, 18.6%), and 6. natural shade grass zone (N = 5, 8.5%). As shown in Table 4, descriptive statistics of mean and standard deviations were

1 B outdoor building sides and surface materials.

2 B indoor building components and surface materials.

3 B external landscape features and surface materials.

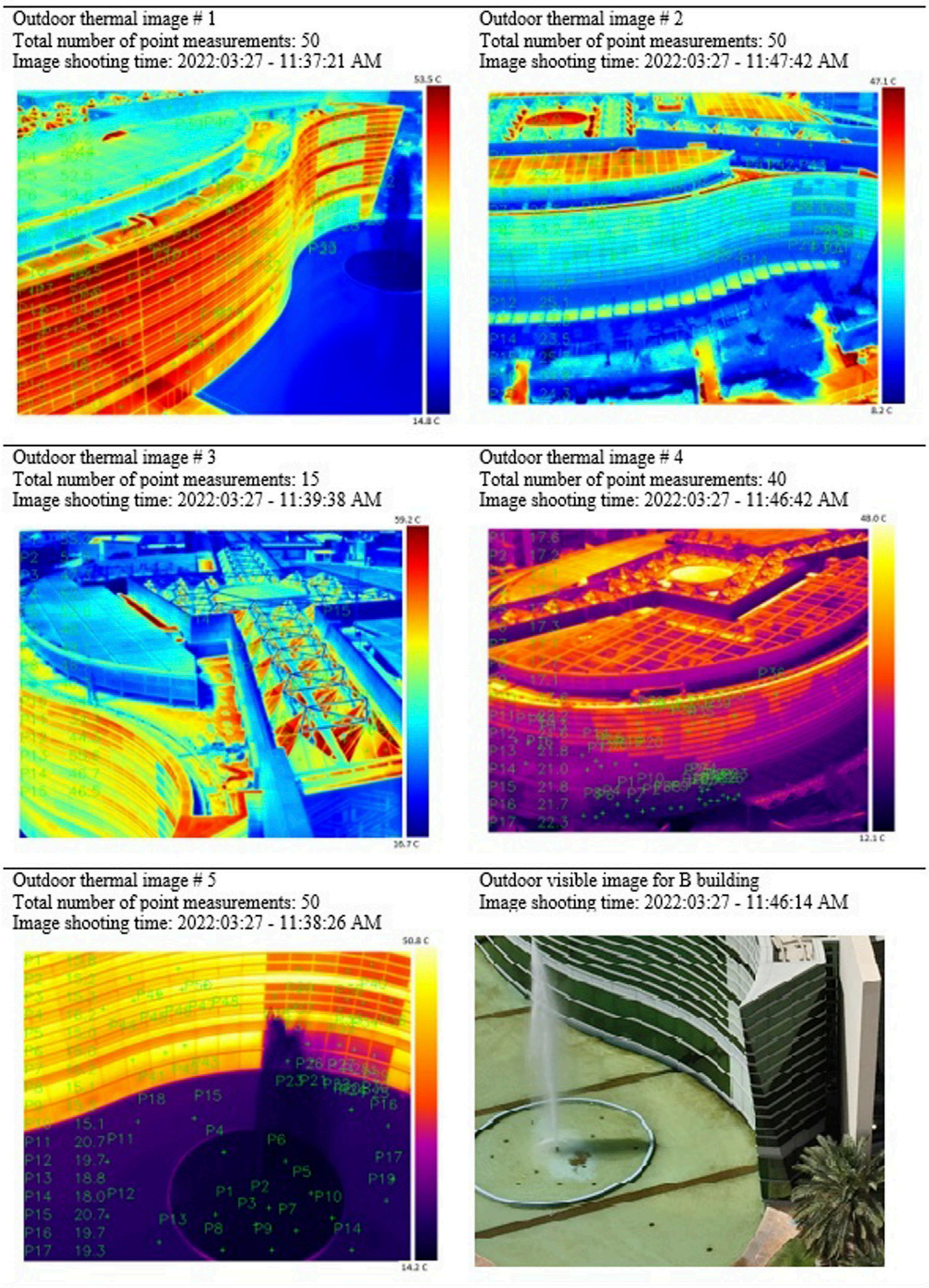

FIGURE 5
Thermal imaging measurements for the B outdoor building.

computed for each group of the previously mentioned variables. Results of the PSSST variable showed that the natural shaded grass surface (NSGS) has the least mean surface temperature (mean = 30.7°C), while the unshaded sand surface (USS) has the greatest mean surface temperature (mean = 48.7°C)—a difference in mean surface temperature of 18°C. The A OBCSM variable comprises seven groups, namely: 1) outside cement roof (N = 10, 10.2%), 2) outside shaded cement (N = 15, 15.3%), 3) outside unshaded cement (N = 10, 10.2%), 4) outside unshaded dark double-glazed spandrel (DGS) glass (N = 7, 7.1%), 5) outside shaded cement wall (N = 10, 10.2%), 6) unshaded gray cement roof (N = 25, 25.5%), and 7) unshaded gray small pebbles roof

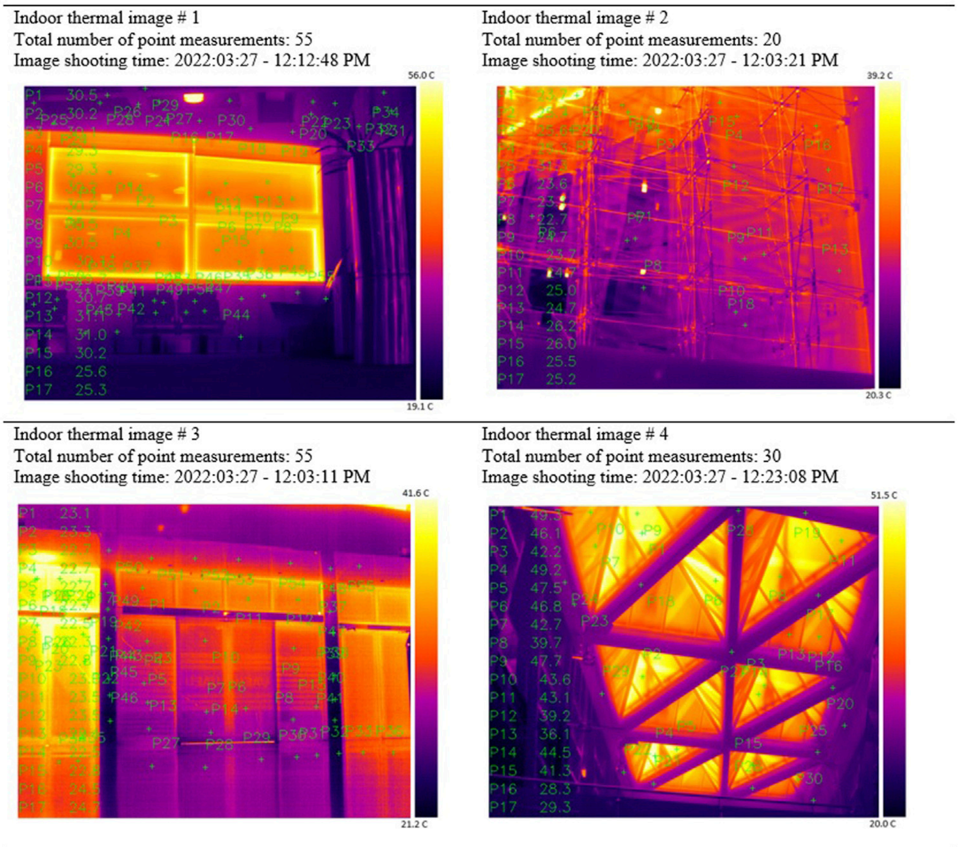

FIGURE 6
Thermal imaging measurements for the B indoor building.

(N = 21, 21.4%). Descriptive statistics results of the A OBCSM revealed that the outside shaded cement (OSC) recorded the lowest mean thermal condition (mean = 20.9°C), while the outside cement roof (OCR) component recorded the highest mean temperature (mean = 51.9°C), with a mean surface temperature variation of 31.0°C.

The B OBSSM variable contains nine groups, namely: 1) outdoor left side dark green glass (N = 25, 21.7%), 2) outdoor left side white glass (N = 10, 8.7%), 3) outdoor left side white cement roof (N = 10, 8.7%), 4) outdoor left side white metal roof (N = 5, 4.3%), 5) outdoor right side DGS dark green glass (N = 25, 21.7%), 6) outdoor right side DGS white glass (N = 10, 8.7%), 7) Outdoor right side white cement roof (N = 10, 8.7%), 8) Outdoor right side white metal roof (N = 5, 4.3%), and 9) Outdoor DGS dark green glass roof (N = 15, 13%). Findings from the B OBSSM descriptive analysis have shown that the outdoor right side made of white DGS glass surface material (located near the trees) has the lowest mean surface temperature (mean = 22.6°C), while the outdoor left side (exposed to direct rays from the rising sun) made of dark green DGS glass surface material has the greatest mean surface temperature (mean = 48.3°C)—having a mean surface temperature difference of 25.6°C.

There are fourteen categories for the B IBCSM variable. First is the indoor dark green DGS glass roof (N = 15, 7.5%; Figure 6—Image 4). The second is the indoor metal roof (N = 15, 7.5%; Figure 6—Image 4). The third is the inside second entrance DGS glass door on the ground floor (N = 15, 7.5%; Figure 6—Image 3). Fourth is the inside entrance DGS glass door on the ground floor (N = 11, 5.5%; Figure 6—Image 3). Fifth is the indoor floor marbles beside the entrance door on the ground floor (N = 10, 5%; Figure 6—Image 3). Sixth is the inside cement wall at the entrance door on the ground floor (N = 19, 9.5%; Figure 6—Image 3). Seventh is the indoor glass roof at the entrance on the first floor (N = 20, 10%; Figure 6—Image 2). Eighth is the indoor glass window on the first floor (N = 15, 7.5%; Figure 6—Image 1). Ninth is the inside cement roof on the first floor (N = 15, 7.5%; Figure 5—Image 1). The tenth is the indoor cement wall on the first floor (N = 15, 7.5%; Figure 5—Image 1). The eleventh is the indoor wooden chairs beside the glass window (on the left side) on the first floor (N = 10, 5%; Figure 6—Image 1). The twelfth is the indoor carpet close to the window on the

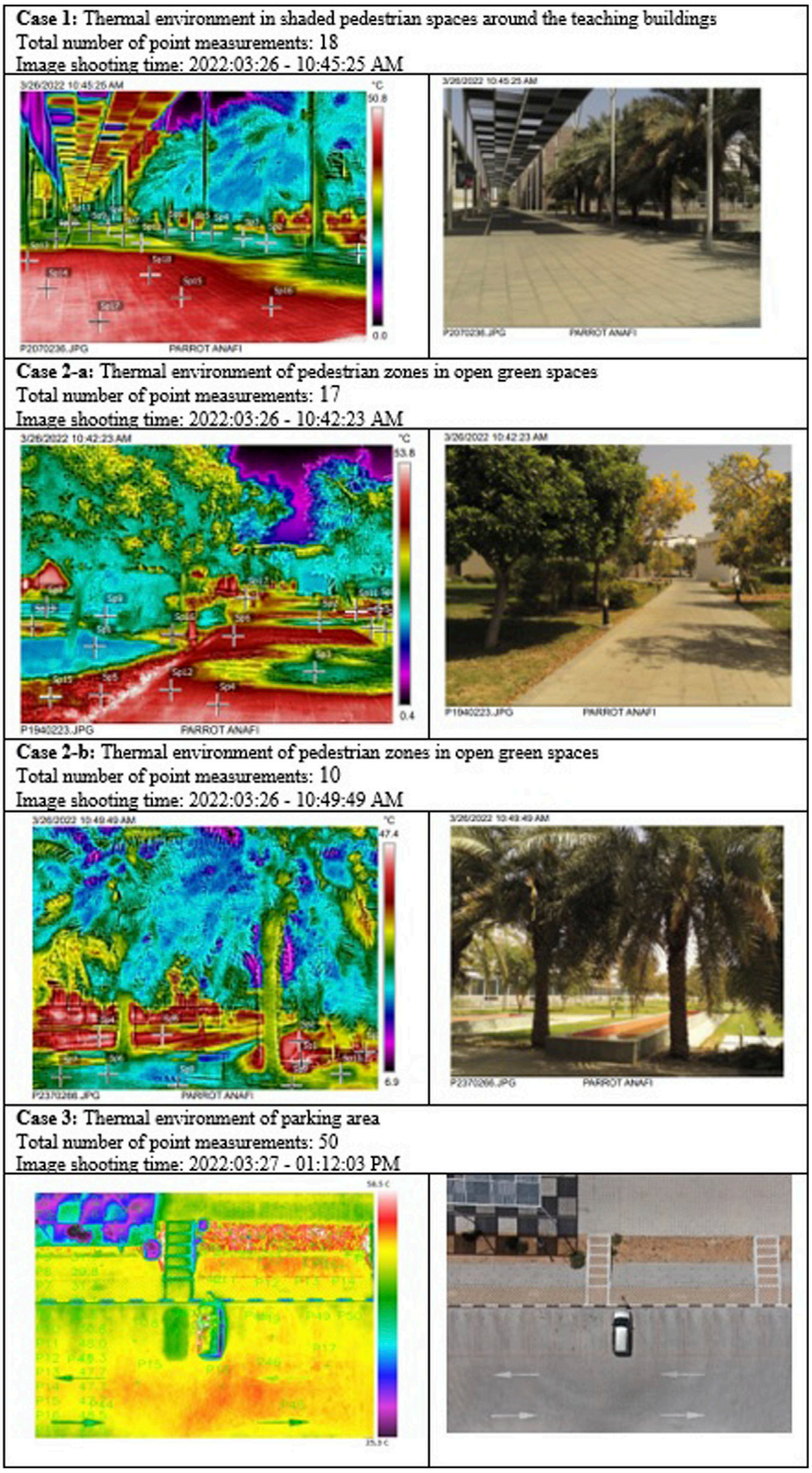

FIGURE 7
Thermal environment analysis in shaded pedestrian areas (Case 1), pedestrian zones in open green spaces (Case 2-a, Case 2-b), and campus parking lot.

TABLE 4 Descriptive statistics of temperatures (°C) by several thermal conditions and by pedestrian spaces shaded surface types (PSSST).

Descriptive statistics of temperatures (oC) by several thermal conditions					
Variables	PSSST	A OBCSM	B OBSSM	B IBCSM	B ELFSM
Mean	38.76	41.11	35.39	26.23	25.09
Std. deviation	7.21	11.47	10.97	5.77	9.36
Std. error of mean	.94	1.16	1.02	.41	.98
Skewness	.35	−.62	.22	2.39	.98
Kurtosis	−1.32	−.95	−1.47	5.74	−.06
Max. temperature °C	52.52	58.60	55.60	49.30	46.70
Min. temperature °C	30.02	19.70	20.50	21.30	15.00
Range	22.50	38.90	35.10	28.00	31.70
Sample size (N)	59	98	115	200	90

Descriptive statistics of temperature (°C) by pedestrian spaces shaded surface types (PSSST)								
Variables	**NSGS**	**USS**	**OSC**	**OCR**	**ICFF**	**IRDGG**	**LSDGG**	**LSWBIP**
Mean temperature °C	30.69	48.75	20.87	51.87	21.69	43.93	45.32	15.32
Std. deviation	.39	2.95	.95	2.58	.14	3.88	.75	.39
Std. error of mean	.17	.89	.25	.82	.04	1.00	.24	.12
Max. temperature °C	31.09	52.52	23.00	55	21.80	49.30	46.70	16.20
Min. temperature °C	30.22	44.17	19.70	47	21.30	36.10	44.30	15.00
Range	.87	8.35	3.30	8	.50	13.20	2.40	1.20
Sample size (N)	5	11	15	10	11	15	10	10

first floor (N = 9, 4.5%; Figure 6—Image 1). Thirteen is the indoor carpet far from the window on the first floor (N = 9, 4.5%; Figure 6—Image 1). Fourteen is the indoor white transparent curtain on the first floor (N = 20, 10%; Figure 6—Image 1). According to the descriptive analysis of the B IBCSM variable, the indoor carpet located a bit away from the window on the first floor (ICFF) has the lowest mean surface temperature (mean = 21.7°C), while the indoor roof made of dark green glass (IRDGG) has the highest mean surface temperature (mean = 43.9°C)—the variation in the mean surface temperature was 22.2°C.

Like the B OBSSM variable, the B ELFSM variable comprises nine categories: 1) right side DGS white glass adjacent to natural shade—trees (N = 10, 11.1%), 2) right side DGS white glass exposed to the Sun (N = 10, 11.1%), 3) Right side DGS white glass near artificial shade (N = 10, 11.1%)., 4) right side dark green DGS glass exposed to the Sun (N = 10, 11.1%), 5) left side water body inside pool ring (N = 10, 11.1%), 6) left side water body outside pool ring (N = 10, 11.1%), 7) left side white DGS glass near water body pool ring (N = 10, 11.1%), 8) Left side white DGS glass at higher floors far from pool ring (N = 10, 11.1%), 9) left side dark green class near water pool (N = 10, 11.1%). Results showed that the dark green DGS glass next to the fountain or pool on the B building's left side (LSDGG) tends to have the highest mean surface temperature (mean = 45.3°C). On the other hand, the water body inside the pool ring on the B building's left side (LSWBIP) showed the least mean surface temperature (mean = 15.3°C). The was a mean surface temperature variation of 30.0°C between the water body inside the pool ring and the dark green glass.

4.3 Normality test

A normality test was conducted to determine the most appropriate metric (parametric or non-parametric) technique for analyzing the data to answer our research questions (Table 5). The variables—thermal conditions of Pedestrian Spaces—Shaded Surface types (PSSST), the temperatures of the A outdoor building components and surface materials (OBCSM), the thermal conditions of the B outdoor building sides and surface materials (OBSSM), the temperatures of the B indoor building components and surface materials (IBCSM), and the thermal conditions of the B external landscape features and surface materials (ELFSM) were all non-normally distributed (p-value < .05) according to both the Kolmogorov and Shapiro statistical tests.

4.4 Kruskal-Wallis H tests

4.4.1 Thermal conditions of pedestrian spaces—shaded surface types (PSSST)

Since the data were not normally distributed, a non-parametric independent sample Kruskal-Wallis Test for Thermal Conditions of Pedestrian Spaces—Shaded Surface types (PSSST) were performed to examine if there is any statistically significant difference in temperature among the shaded surface materials/types for pedestrians. The test result (Table 5) reveals a significant statistical difference between some shaded surface types with respect to Temperature (Test

TABLE 5 Normality test of the variables and independent samples Kruskal-Wallis Test for differences for PSSST and BCSM with respect to temperature.

Normality test of the variables						
Variables	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
PSSST temperatures (C)	.153	59	.002	.894	59	<.001
PSSST grouping variable	.205	59	<.001	.899	59	<.001
A OBCSM temperatures (C)	.174	98	<.001	.891	98	<.001
A OBCSM grouping variable	.225	98	<.001	.869	98	<.001
B OBSSM temperatures (C)	.134	115	<.001	.902	115	<.001
B OBSSM grouping variables	.131	115	<.001	.905	115	<.001
B IBCSM temperature (C)	.202	200	<.001	.696	200	<.001
B IBCSM grouping variables	.098	200	<.001	.936	200	<.001
B ELFSM temperatures (C)	.184	90	<.001	.863	90	<.001
B ELFSM grouping variables	.113	90	.007	.931	90	<.001
Independent samples Kruskal-Wallis test for differences for PSSST and BCSM with respect to temperature						
Variables	**Total N**	**Kruskal-Wallis H**	**Mean rank (highest)**	**Mean rank (lowest)**	**df**	**Asymptotic Sig. (2-tail)**
PSSST	59	45.316	52.00	7.60	5	<.001
A OBCSM	98	85.666	80.60	8.00	6	<.001
B OBSSM	115	95.709	95.60	14.10	8	<.001
B IBCSM	200	182.427	193.00	12.36	13	<.001
B ELFSM	90	86.011	85.50	5.55	8	<.001

[a]Lilliefors significance correction.

Statistics = 45.316, df = 5, $p < .001$). Mean rank = 52.0 indicates that the Unshaded Sand surface has the highest temperature, followed by the Unshaded Cement surface type (mean rank = 38.3) and Unshaded Grass (Mean rank = 29.55). The test result shows that the Natural Shade Grass recorded the lowest temperature with a mean rank of 7.6, followed by the Natural Shaded Cement surface (mean rank = 10.2) and the Artificial Unshaded Cement surface (mean rank = 24.7). Overall, the results showed that the Natural Shaded Grass surface tends to have the most tolerable heat environment, while the Unshaded Sand surface has the most unfriendly thermal environment, with a huge mean temperature difference of 44.4°C. Therefore, shading the area with natural grass or trees as much as possible is the most efficient way to create a comfortable pedestrian zone.

The Kruskal Wallis H test results also showed a significant statistical difference between some groups of the grouping variables PSSST; thus, a pairwise post-hoc test (Table 6) was run to identify which paired samples surface types have temperatures that are statistically significantly different at .05 significance level. The post-hoc test results (Table 6) for the PSSST grouping variable showed that out of the fifteen paired samples, only the following two paired samples were not statistically significant: 1. The Artificial Shaded Cement surface (ASC) and Unshaded Grass surface (UG) ($p = .159 > .05$); 2. The Natural Shaded Cement surface (NSC) and the Natural Shaded Grass surface (NSG) ($p = .396 > .05$) at .05 level of significance. In other words, all the paired samples of the shaded surface types showed a statistically significant difference in temperature except for 1. ASC and UG, and 2. NSC and NSG. This could partly imply that the difference in mean temperatures of naturally shaded pedestrian spaces tend to be statistically insignificant in the Spring season at UAEU campus.

4.4.2 A outdoor building components and surface materials (OBCSM)

The Kruskal-Wallis H test results (Table 5) for the exterior A building components (e.g., roof, wall) and surface material types/colors (e.g., glass, cement, small pebbles) grouping variable reveal a significant statistical difference between some building components and surface material types/colors with respect to Temperature (Test Statistics = 85.666, df = 6, $p < .001$). According to the mean ranks of the grouping variable OBCSM, the outside cement roof component (mean rank = 80.6) registered the highest level of heat, followed by the unshaded roof component made of small gray pebbles (mean rank = 80.4) and the unshaded roof consisting of gray cement (Mean rank = 57.6). In addition, the test result shows that the outside shaded cement recorded the lowest temperature (mean rank = 8.0), followed by the exterior shaded dark DGS glass surface, which has a mean rank of 20.21. Next is the shaded outside wall made of cement (mean rank = 28.4). It is important to note that the data (thermographic images) were captured during the daytime in Spring, precisely between 12:42 p.m. and 1: 41 p.m. on 27 March 2022.

TABLE 6 Pairwise Comparisons of the PSSST, OBCSM (A), OBSSM (B), IBCSM (B), and ELFSM (B) Grouping Variables in terms of Temperature (T).

Grouping variable	Sample1—Sample 2	Test statistics (U)	Std. Test Stat. (z)	Sig. (2-tail)
PSSST	Artif. Shade cement and unshaded grass	19.00	−1.407	.159
	Natural Shade cement and Natural shade grass	20.00	−.850	.396
OBCSM (A)	Roof outside Cemt. and unshaded roof gray small pebbles	103.50	−.063	.949
OBSSM (B)	Left side dark green glass and roof outside dark green glass	176.500	−.308	.758
	Left side white glass and left side roof white cement	48.500	−.113	.910
	Left side white glass and right-side roof white metal	14.000	−1.347	.178
	Left side roof white cement and left side roof white metal	11.000	−1.715	.086
	Left side roof white cement and right-side roof white metal	20.000	−.612	.540
	Left side roof white metal and right-side roof white cement	16.000	−1.103	.270
	Left side roof white metal and right-side roof white metal	8.500	−.838	.402
	Right side dark green glass and right-side roof white cement	100.000	−.913	.361
	Right-side white glass and right-side roof white cement	48.500	−.114	.910
	Right-side roof white cement and right-side roof white metal	11.000	−1.716	.086
IBCSM (B)	Indoor second GED GF and indoorfloor marble beside EDGF	57.000	−1.004	.315
	Indoor second GED GF and indoor wooden chairs beside the GWFF	45.000	−1.679	.093
	Indoor single GED GF and indoor entrance GRFF	70.500	−1.638	.101
	Indoor single GED GF and indoor cement Roof FF	61.000	−1.126	.260
	Indoor single GED GF and indoor cement wall FF	71.500	−.577	.564
	Indoor floor marble beside EDGF and indoor cement wall at the EDGF	62.000	−1.521	.128
	Indoor floor marble beside EDGF and indoor wooden chairs beside GWFF	25.000	−1.950	.051
	Indoor floor marble beside EDGF and indoor carpet close to the WFF	35.000	−.828	.408
	Indoor cement wall at the EDGF and indoor carpet close to the WFF	76.500	−.445	.656
	Indoor cement wall at the EDGF and indoor carpet far from the WFF	60.000	−1.939	.052
	Indoor entrance GRFF and indoor cement roof FF	125.500	−.819	.413
	Indoor entrance GRFF and indoor cement wall FF	93.500	−1.889	.059
	Indoor cement roof FF and indoor cement wall FF	80.500	−1.333	.183
ELFSM (B)	RSWG near trees and RSWG near artificial shade	25.500	−1.873	.061
	RSDGG exposed to Sun and LSWG near water pool ring	36.500	−1.023	.306

For the OBCSM grouping variable, the post-hoc test results (Table 6) showed that out of the twenty-one paired samples, and only one paired sample did not show a statistically significant difference with regards to temperature—Roof Outside Cement (ROC) and Unshaded Roof Gray small pebbles (URGSP) (p = .949 > .05) at .05 level of significance. In other words, all the paired samples of the building components and surface material types/colors showed a statistically significant difference in temperature except for the paired sample (the outside roof comprising of cement and the unshaded roof made of small gray pebbles) of A building.

4.4.3 B outdoor building sides and surface materials (OBSSM)

Similarly, an independent sample Kruskal-Wallis Test for the exterior of the B building (grouping variable) was used to examine if there was a statistically significant variation in temperature between the building sides (e.g., left side, right side, etc.) and surface material types/colors (e.g., metal, glass, cement, etc.). The test result (Table 5) shows a statistically significant difference in temperature between some building sides and surface material types/colors (Test Statistics = 95.709, df = 8, p .001). The outdoor left side made of dark green DGS glass surface material registered the highest amount of heat (mean rank = 95.6), followed by the outside roof made of dark green DGS glass surface material (mean rank = 93.1), and the outside left side made of white DGS glass (Mean rank = 63.2). Furthermore, the outside right side made of white DGS glass surface material (located near the trees) recorded the lowest temperature (Mean rank = 14.1), followed by the exterior roof on the right side made of white cement surface material with a mean rank of 26.4, and the external dark green DGS glass on the right side (mean rank of 28.1). It is worth noting that the data (thermographic images) were taken between 11:37 a.m. and 11:47 a.m. on 27 March 2022.

The post-hoc test results (Table 6) of the grouping variable OBSSM for B building showed that ten out of the thirty-six paired samples revealed a non- significant statistical difference with regards to temperature 1. Left Side Dark Green DGS Glass and Roof Outside Dark Green DGS Glass (p = .758 > .05); 2. Left Side White DGS Glass and Left Side Roof White Cement (p = .910 > .05); 3. Left Side White Glass and Right-Side Roof White Metal (p = .178 > .05); 4. Left Side Roof White Cement and Left Side Roof White Metal (p = .086 > .05); 5. Left Side Roof White Cement and Right-Side Roof White Metal (p = .540 > .05); 6. Left Side Roof White Metal & Right-Side Roof White Cement (p = .270 > .05); 7. Left Side Roof White Metal and Right-Side Roof White Metal (p = .402 > .05); 8. Right Side Dark Green DGS Glass and Right-Side Roof White Cement (p = .361 > .05); 9. Right-Side White Glass and Right-Side Roof White Cement (p = .910 > .05); 10. Right-Side Roof White Cement and Right-Side Roof White Metal (p = .086 > .05) at .05 level of significance. In other words, except for the ten mentioned paired samples, all the other paired samples of the B building sides and surface material types/colors showed a statistically significant difference in temperature.

4.4.4 B indoor building components and surface materials (IBCSM)

An independent sample Kruskal-Wallis Test was performed to analyze if there was a statistically significant difference in temperature among the building components (example: window, floor, wall, roof, etc.) and surface materials (example: cement, marble, glass, carpet, etc.) inside B building. The test result (Table 5) shows a statistically significant difference in temperature between some of the indoor building components and surface materials (Test Statistics = 182.427, df = 13, $p < .001 < .05$). The roof inside, made of dark green glass, indicated the highest temperature (mean rank = 193.0). This is followed by an indoor DGS glass window on the first floor that receives direct rays from the rising sun, which registers a mean rank of 175.1. Next in rank is the indoor roof made of metal, with a mean rank of 162.8. Following the indoor metal roof is the indoor white transparent curtain hung on the window on the first floor (mean rank = 144.3). On the other hand, the indoor carpet located a bit far from the window on the first floor had the lowest temperature with a mean rank of 12.4. This is followed by the indoor cement wall at the entrance door found on the ground floor, registering a mean rank of 29.8. The inside carpet close to the window on the first floor showed the third lowest temperature with a mean rank = of 34.1, followed by indoor floor marble beside the entrance door on the ground floor (mean rank = 44.1). It is important to point out that all the thermographic images of the inside B building components and surface materials were taken between 12:03 p.m. and 12:33 p.m. on 27 March 2022.

The post-hoc test results (Table 6) of the grouping variable IBCSM for B building showed that thirteen out of the ninety-one paired samples revealed a non-significant statistical difference regarding their temperatures (i.e., 1. The interior second DGS glass entrance door, ground floor and the inside floor marble beside the entrance door ground floor (p = .315 > .05); 2. The inside second DGS glass entrance door, ground floor and the indoor wooden chairs beside the DGS glass window, first floor (p = .093 > .05); 3. The interior DGS glass entrance door, ground floor and the indoor entrance DGS glass roof, first floor (p = .101 > .05); 4. The inside DGS glass entrance door, ground floor and the indoor cement roof, first floor (p = .260 > .05); 5. The interior DGS glass entrance door, ground floor and the indoor cement wall, first floor (p = .564 > .05); 6. The interior floor marble beside the entrance door, ground floor and the indoor cement wall at the entrance door, ground floor (p = .128 > .05); 7. The indoor floor marble beside the entrance door, ground floor and the inside wooden chairs beside the DGS glass window, first floor (p = .051 > .05); 8. The interior floor marble beside the entrance door, ground floor and the indoor carpet close to the window, first floor (p = .408 > .05); 9. The indoor cement wall at the entrance door, ground floor and the indoor carpet close to the window, first floor (p = .656 > .05); 10. The indoor cement wall at the entrance door, ground floor and the indoor carpet far from the window, first floor (p = .052 > .05); 11. The indoor DGS glass roof at the entrance, first floor and the indoor cement roof, first floor (p = .413 > .05); 12. The indoor DGS glass roof at the entrance, first floor and the indoor cement wall, first floor (p = .059 > .05); 13. The indoor cement roof, first floor and the indoor cement wall, first floor (p = .183 > .05) at .05 level of significance. In other words, except for the thirteen mentioned paired samples, all the other paired samples of the B internal building components and surface material types showed a statistically significant difference in temperature.

4.4.5 B external landscape features and surface materials (ELFSM)

An independent sample Kruskal-Wallis Test for the landscape features around B building (grouping variable) was conducted to examine if there was a statistically significant variation in temperature among the surface material types/

colors (e.g., glass, cement, etc.) and the external landscape features (e.g., trees, artificial shades, fountain, etc.) in the vicinity of B building. The test result (Table 5) shows a statistically significant difference in temperature between some of the surface materials and the outdoor landscape features (Test Statistics = 86.011, df = 8, $p < .001 < .05$). The dark green DGS glass near the water pool/fountain on the left side of the B building registered the highest temperature (mean rank = 85.5). This is followed by the white DGS glass on higher floors far from the pool ring/fountain with a mean rank of 75.5, and the white DGS glass near water body pool ring with a mean rank of 60.5. Conversely, the water body inside the pool ring on the left side of the building recorded the lowest temperature with a mean rank = 5.5, followed by the white DGS glass near the artificial shade located on the right side of the building (mean rank = 18.0). Next comes the white DGS glass close to the trees (natural shade) which has a mean rank of 22.9. It is worth noting that the data (thermographic images) were taken between 11:38 a.m. and 11:46 a.m. on 27 March 2022.

The post-hoc test results (Table 6) for the ELFSM (B) grouping variable revealed that only two of the twenty-one paired samples did not show a statistically significant difference in temperature i.e., 1. The white DGS glass near the natural shade (trees) and white DGS glass near the artificial walkway shade are both located on the right side of B building ($p = .061 > .05$); 2. The dark green DGS glass is exposed to sunlight on the right side of B building, and the white DGS glass near the water fountain ring on the left side of the building ($p = .306 > .05$) at a 5% level of significance. In other words, except for the two paired samples described above, the temperatures of all the paired external landscape features and surface materials samples of the B building have a statistically significant variation in thermal conditions.

In this study, it could be noted from the results of the various thermal image analysis that almost all the indoor and outdoor landscape features, building components, and surface materials of the A and B buildings as well as the pedestrians' spaces in the UAEU main campus have significant variations in their thermal mass. Utilizing high thermal mass materials along with night cooling is a more sustainable solution to reduce the risk of overheating for many building types, including commercial structures (Farooq et al., 2021). Thermal mass is the capability of a material to absorb, hold, and emit heat. Heat is taken in and stored by materials like tiles, bricks, and concrete. As a result, they do have a high level of thermal mass. Timber and cloth, for example, have little thermal mass because they do not absorb and store heat (Reardon et al., 2020).

Also, it is crucial to include thermal lag when evaluating thermal mass. Thermal lag refers to the rate at which a substance collects and emits heat. Materials that absorb and discharge heat slowly have long thermal lag times (such as concrete and brick), whereas materials with short thermal lag times (such as steel) absorb and release heat rapidly. Identifying materials with high thermal mass is essential because when utilized properly, high thermal mass materials can greatly improve comfort while lowering energy use in buildings. Thermal mass functions as a thermal battery, averaging out daylight variations to moderate internal temperatures. The thermal mass may absorb heat from direct sunshine in the daytime during the winter. At night, it transmits this heat back into the building (Reardon et al., 2020).

Thermal mass could be employed to keep a building cool in the summer. If the light is unable to reach the mass (for example, through shadowing), the mass will absorb heat from the interior of the house. The stored energy can then be drawn out overnight by allowing cool breezes and convection currents to flow over the thermal mass. On the other hand, poor thermal mass use can impair comfort and boost energy use. Insufficient thermal mass can absorb the body heat on a cold winter night or radiate heat all night as inhabitants try to rest during summertime. Baggs and Mortensen (2006) elucidated that in most climate zones, adding thermal mass elements to buildings can help reduce the amount of energy used for heating and cooling, as well as the environmental effects of burning fossil fuels for energy production. It can also lower costs, increase comfort, and reduce or even eliminate the need for air conditioning.

4.4.6 Spearman's rank correlations between the overall temperatures of B OBSSM, B IBCSM, and B ELFSM

Non-normal distributions were detected for three variables of the B building (B OBSSM, B IBCSM, and B ELFSM) had non-normal distributions (Table 7). Therefore, the link between these factors, which should not be interpreted as cause-and-effect correlations, was examined using Spearman's rank correlation (Table 8). According to the results of rank correlation analysis, the B OBSSM variable was most significantly correlated with the B ELFSM (=−.488, p .01) and least significantly correlated with the B IBCSM (= −.460, p .01). The strength of both associations was moderate with negative direction according to the coefficient of correlation (ρ). This implies that an increase in the overall temperature of the B OBSSM variable, for instance, decreases the B IBCSM variable and *vice versa*. Likewise, the B IBCSM variable exhibited strongest correlation with B ELFSM ($\rho = .690$, $p < .01$) and the weakest correlation with B OBSSM ($\rho = -.460$, $p < .01$). According to the coefficient of correlation (ρ), the association between B IBCSM and B ELFSM was positive and slightly strong, indicating a rise in the overall heat of the ELFSM of B building leads to a rise in the overall temperature of the B IBCSM and *vice versa*. On the other hand, the relationship between B IBCSM and B OBSSM was negative and moderately strong according to the coefficient of correlation (ρ). All these bivariate associations were statistically significant at .01 level of significance ($p < .01$), and the sample size of each variable was N = 90.

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TABLE 7 Normality test of B OBSSM, B IBCSM, and B ELFSM.

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
B OBSSM temperatures °C	.145	90	<.001	.884	90	<.001
B IBCSM temperature °C	.199	90	<.001	.812	90	<.001
B ELFSM temperatures °C	.184	90	<.001	.863	90	<.001

[a]Lilliefors significance correction

TABLE 8 Spearman's bivariate rank correlations between the overall temperatures of B OBSSM, B IBCSM, and B ELFSM.

Variables	B OBSSM Temp. (°C)	B IBCSM Temp. (°C)	B ELFSM Temp. (°C)
B OBSSM temperature (°C)	1.000	−.460**	−.488**
B IBCSM temperature (°C)	−.460**	1.000	.690**
B ELFSM temperature (°C)	−.488**	.690**	1.000
N	90	90	90

**Correlation is significant at the .01 level (2-tailed).

5 Discussion

Among the certain threats arising due to climate change and global warming, the devasting effect of heat agglomeration has caught significant attention during the past decades. The major impact of a rise in ambient temperature has intensified the peak cooling load demand of buildings as well as caused poor personal thermal management of occupants during outdoor activities. Therefore, assessing the thermal environment of buildings and outdoor structures is essential to provide sustainable solutions to overcome these challenges by incorporating advanced building materials and innovative structural designs. However, numerical estimation is restricted in showcasing and predicting accurate temperature variations over time due to abrupt changes in weather conditions, occupancy rate, diversity in building materials, and variation in buildings orientation structures. Therefore, employing thermal infrared imaging cameras and UAVs are proven to be reliable, cost-effective, and efficient methods of visualizing real-time situations under varying conditions of heat stress.

This study explores the application of thermal imagery-based cameras on UAVs for mapping urban structures, and the flight missions were conducted throughout the weekend of 26 and 27 March 2022, at the UAEU main campus to explore the potential of using UAVs for thermal photogrammetric mapping in order to help track and categorize heat rates in buildings according to their orientation and material composition (such as glass, cement, sand, etc.). Additionally, the spatial distribution of thermal comfort is assessed and analyzed based on the structural configurations of selected pedestrian areas and parking lots, such as shaded, unshaded, and areas near plants or trees. The analysis results for thermal conditions of shaded/unshaded surface types for pedestrian space revealed that the natural shaded grass surface tends to have the most tolerable heat environment (mean rank = 7.6). In contrast, the unshaded sand surface has the most unfriendly thermal environment (mean rank = 52.0), with a difference in mean surface temperature of 18.0°C. This finding corroborates with the study by Zhao et al. (2020), who found that between shaded and unshaded portions of the mean radiant temperatures (MRT), there was a temperature differential of more than 3.0°C. The MRT readings were lower at the measuring sites close to vegetation.

The analysis results of outdoor building components and surface materials have shown that the exposed cement roof component registered the highest level of heat (mean rank = 80.6), while the shaded cement outside recorded the lowest thermal condition (mean rank = 8.0), with a mean surface temperature variation of 31°C. In addition, the statistical findings of the B outdoor building sides and surface materials showed that the outdoor left side (exposed to direct rays from the rising sun) made of dark green DGS glass surface material has the highest amount of heat (mean rank = 95.6), while the outer right side made of white DGS glass surface material (located near the trees) recorded the lowest temperature (Mean rank = 14.1), having a mean surface temperature difference of 26°C. Likewise, results from the analysis of the B indoor building components and surface materials showed that the roof inside, made of dark green DGS glass, has the highest temperature (mean rank = 193.0), while the indoor carpet located a bit far from the window on the first floor had the lowest temperature with a mean rank of 12.36. The mean surface temperature difference between the roof inside and the carpet is 22.0°C.

These findings are consistent with the views of Massetti et al. (2019) and Djekic et al. (2018). According to Massetti et al. (2019), on summer days, thermal distress was most noticeable over exposed asphalt, and because gravel has a higher reflectivity, thermal discomfort was even more apparent compared to exposed gravel. Shaded surfaces, however, exhibited significant reductions in thermal stress. Over the course of the fall season, incoming solar radiation declines, yet direct radiation under the steadily thinning forest canopy rises. The difference in asphalt surface temperature between exposed and shaded areas decreases substantially from roughly 20.0°C–3.0°C because of this lessened shading effect. Djekic et al. (2018) observed that surfaces exposed to sunlight and shaded surfaces exhibit the largest temperature variations, which vary from 2.0°C to 20.0°C. The users' thermal comfort is impacted by temperature differences (8.0°C) between the hottest and coolest materials (rough black granite and smooth red granite), the hottest material and grass (22.0°C), and shaded and unshaded places (20.0°C). Additionally, surfaces exposed to sunlight during the day maintained a greater temperature than surfaces that were shaded or partially shaded during the day, even after overnight cooling down.

For the B external landscape features and surface materials, the results revealed that the dark green DGS glass near the water pool/fountain on the left side of the B building tends to have the most unfriendly external heat environment (mean rank = 85.5). Conversely, the water body inside the pool ring on the left side of the building tends to have the friendliest thermal environment, with a mean rank = 5.5. The difference in mean surface temperature of dark green DGS glass and the water body inside the pool ring was 30.0°C. This result further elucidates that the thermal comfort of practically every indoor and outdoor landscape feature, structural component, and surface material in the A and B buildings, as well as the pedestrian spaces, varies significantly. There were substantial positive and negative correlations among the overall temperature variables of B OBSSM, B IBCSM, and B ELFSM, according to Spearman's rank correlations.

The findings above indicate that the presence and type of shade (e.g., natural shaded grass surface vs. unshaded sand surface), the type and color of building surface material (e.g., dark green DGS glass surface material vs. white DGS glass surface material), and building design and orientation (e.g., left direction vs. right direction) have a significant impact on the thermal environment of buildings, and pedestrians' space in the context of UAEU campus during the Spring season. It also indicates that the comfort and thermal environment of outdoor pedestrians, building components, and surface materials are improved by shade, vegetation, and the structural design and position of a building (Lin and Matzarakis, 2008; Yin et al., 2022; Kang et al., 2020). However, it is crucial to keep in mind that the placement and orientation of buildings, the patterns and types of vegetation (such as grass, shrubs, and trees), variation in solar irradiance, and ambient conditions altogether affect the thermal comfort of occupants as well as the load profile of buildings.

6 Conclusion

In line with SDG 11 goal of providing sustainable, safe, and resilient human settlement and urban development, this study explores the application of thermal imagery-based cameras on UAVs for thermal photogrammetric mapping, assisting in the monitoring and classifying of heat rates based on orientation and building components, such as glass, cement, sand, etc. Furthermore, the spatial distribution of surface temperatures is evaluated and analyzed for selected pedestrian spaces and parking lots based on their structural configurations, such as shaded, unshaded, and areas near plants or trees.

The analysis results for thermal conditions of shaded/unshaded surface types for pedestrian space revealed that the natural shaded grass surface has the most tolerable heat environment (mean rank = 7.6), while the unshaded sand surface has the most unfriendly thermal environment (mean rank = 52.0), with an 18°C difference in mean surface temperature. Furthermore, outdoor building components and surface materials revealed that the exposed cement roof component registered the highest level of heat (mean rank = 80.6), whereas the shaded cement outside recorded the lowest thermal condition (mean rank = 8.0), with a mean surface temperature variation of 31.0°C. Meanwhile, indoor building components and surface materials revealed that the dark green DGS glass roof had the highest temperature (mean rank = 193.0). In contrast, the indoor carpet placed a bit further from the window on the first level floor had the lowest temperature with a mean rank of 12.36. The mean surface temperature difference between the roof inside and the carpet is 22.0°C. The external landscape elements and surface materials are investigated, and the results indicate that the dark green DGS glass near the water pool/fountain has the most unfavorable heat environment (mean rank = 85.5). On the other hand, the water body within the pool ring on the left side of the building has the most tolerable thermal environment, with a mean rank = 5.5.

The findings demonstrate that the building load profile and pedestrian comfort are influenced by several factors, including local atmospheric conditions, building material and orientation, shading and the presence of trees in the targeted area. Literature suggests several heat mitigation strategies, such as opting for optimized orientation with minimal south facing and excellent ventilation, planting vegetation, such as planting trees, green roofs, and walls:

due to their capability of heat mitigation by enabling solar reflectivity, evapotranspiration, and blocking solar irradiance. Furthermore, high albedo materials, such as reflective/radiative coatings and paints for glass windows, walls and roofs, as well as pedestrian pathways, are potential candidates for improving outdoor thermal comfort and reducing the peak load profile of buildings by simultaneously minimizing solar radiation absorption and maximizing emitted radiation. To decrease urban heat agglomeration, it is necessary to examine the effect of trees on wind speed and direction and to develop innovative materials with nearly 100% solar reflectivity and maximum emissivity. However, one of the potential challenges of employing reflective/radiative paints on walls and rooftops is that they might cause discomfort by increasing the heat load during summer. Therefore, self-adaptive heating/cooling materials should be introduced to overcome such limitations. Furthermore, since the meteorological data has a significant role in the desired level of personal comfort, future research experiments should be conducted across diverse climates to find a correlation between heat mitigation strategies and climatic conditions.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

KA has contributed on the formation of the study proposal and research supervision, drone flying plan and experiment, manuscript writing, imagery analysis, statistical data analysis and interpretation, and publication submission. SS has helped with manuscript writing, statistical data analysis and interpretation. AR helped with 3D model creation, camera calibration and drone flying plan.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The handling editor MS declared a shared affiliation with the author KA, SS, ER at the time of review.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbuil.2022.1035546/full#supplementary-material

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Nomenclature

IGUs Insulating glass units

TIR Thermal infrared

UAV Unmanned aerial vehicle

IRT Infrared thermography

ITT Infrared thermography technique

IOP Interior orientation parameters

DGS Double glazed spandrel

SP Spot measurement

SPSS Statistical Package for the Social Sciences

PSSST Pedestrian Spaces Shaded Surface types

A OBCSM A outdoor building components and surface materials

B OBCSM B outdoor building components and surface materials

B IBCSM B indoor building components and surface materials

B ELFSM B external landscape features and surface materials

B OBSSM B outdoor building sides and surface materials

NSGS Natural shaded grass surface

OSC Outside shaded cement

OCR Outside cement roof

ICFF Indoor carpet located a bit away from the window on the first floor

IRDGG Indoor roof made of dark green glass

LSDGG Dark green DGS glass next to the fountain or pool on the B building's left side

LSWBIP The water body inside the pool ring on the B building's left side

ASC Artificial Shaded Cement surface

NSC Natural Shaded Cement surface

ROC Roof Outside Cement

URGSP Unshaded Roof with Gray small pebbles

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Post-pandemic planning: Do we have enough and efficient access to parks?

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Introduction: The COVID-19 pandemic has placed neighborhood parks as a key asset in mitigating the negative implications of extended lockdowns, when parks turned into a sanctuary for residents. With increased scholarly work focusing on developing pots-pandemic neighborhoods, providing access to community parks *via* efficient routes, is central to such debate. Network connectivity provides a comprehensive assessment of the efficiency of network systems.

Methods: A total of 16 samples, from the city of Abu-Dhabi, have been selected to study their network connectivity, with regard to accessing parks. Three distance-based connectivity measures are used: the pedestrian route directness (PRD), the count of redundant routes Redundancy Count (RC), and the route redundancy index (RI). The samples reflect different street's typologies and their urban form attributes are quantified.

Results and Discussion: Connectivity analyses results are interrupted with regard to the quantified physical attributes. Findings indicate that gridded, and semi-gridded layouts provide more direct routes to parks, but less route's redundancy. Conversely, interlocked, and fragmented networks, when having sufficient intersection densities, have less direct routes but more redundancy. The inclusion of alleyways proved to alter typologies into gridded ones and improve both route directness and redundancy. The majority of the selected samples reported sufficient levels of route directness. The current design and planning guidelines, implemented by the Department of Transport and Municipalities are overly descriptive with regard to how neighborhood parks are accessed; therefore, the study's methodology provides a possible more evidence-based approach to policy development.

KEYWORDS

connectivity, street networks, COVID-19, route directness, route redundancy, Abu-Dhabi, parks, urban form

1 Introduction

The restricted mobility and social gathering measures, mandated during the recent COVID-19 pandemic, caused mass disruption to normal lives and active living (Caroppo et al., 2021); this included work (Espitia et al., 2022), education (Onyema et al., 2020), healthcare (Bashshur et al., 2020) and most notably urban living (Mouratidis and Papagiannakis, 2021). Jáuregui et al. (2021) discussed, in one of the world's leading medical journals, the Lancet, the critical role of urban design and planning in offsetting the negative ramifications of possible future pandemic scenarios. He argued for accelerating change towards designing cities that are highly conducive to active mobility, which prioritize parks and public open spaces as key assets to post-pandemic urban living. Access to parks and urban green spaces, during the pandemic, helped millions of people maintain their mental and physical health (Slater et al., 2020). Many studies highlighted the impact of the built environment on accommodating easier access to parks (Lai et al., 2020; Megahed and Ghoneim, 2020).

The relation between physical activity and the built environment, therefore, has been explored to further advance sustainable urban design agendas, centered around pedestrian needs. New-urbanism ideals with regard to neighborhoods planning and design, for example, is focused on locating daily necessities within walking distance to reduce car dependency, by ensuring that streets, pedestrian routes, and sidewalks are highly connected (U.S. Department of Housing and Urban Development, Congress for the New Urbanism, 2002). Handy et al. (2002), in discussing which features of the built environment impact residents' physical activity and wellbeing, pointed out that walkable environments have certain attributes in terms of density, land-use mix, and street systems. Specifically, walkable streetscapes showed consistently higher degrees of connectivity, which can be defined as "the directness and availability of alternative routes from one point to another within a street network" (Handy et al., 2002). During the pandemic, Wargent and Talen (2021) highlighted how the extended lockdown durations has motivated people to rediscover their neighborhoods by stating that "Now many of us will be more aware of how walkable our neighborhoods are and more attuned to the importance of access to local amenities" (p.2). Pots-pandemic neighborhoods design agendas, therefore, should emphasize highly connected street networks that ensures active mobility to parks and urban green spaces.

This study addresses the impact of streets' network connectivity, in the city of Abu-Dhabi, on ensuring efficient travel to neighborhood parks. A total of 16 samples, grouped into six typologies, have been selected from different neighborhoods to evaluate the connectivity of street networks within 1-km network-based distance from local parks. Connectivity is evaluated using three measures. The first is the Pedestrian Route Directness (PRD) which assesses whether routes, connecting residential plots to the park, support travel at short distances; the second is the Redundancy Count (RC) which return the count of alternative routes available for travel at distances with minimum deviations from the shortest route; the third is the Redundancy Index (RI) which provides insights on the efficiency of the alternative routes with regard to their distance deviations, from the absolute shortest path. Paydar and Kamani Fard (2021) study on the hierarchy of walking needs, during the pandemic, revealed that people's preferences were concerned with minimizing crowds contact and deviations from the shortest path. Therefore, it can be argued that route redundancy emerges as a decisive factor in post-pandemic cities. This study offers two unique contributions to the literature. First, the article uses street network connectivity, in terms of both route directness and route redundancy, to assess whether current street typologies in Abu-Dhabi neighborhoods provide efficient routes to connect the residential plots to their local park. Second, the article complements network analysis results with conventional morphological analysis that quantifies the physical attributes of the network system in terms of: network density, percentages of 4-way intersections, intersection density, average distance between intersections, the average block size, the average distance to the park, and the network hierarchical composition (e.g., percentages of arterials and/or collectors). This allows the depiction of the built environment with a critical perspective, thus informing policy and the process of building better walkable communities. Key research questions answered by this article: 1) Are Abu Dhabi's neighborhood network system designed to promote route directness and choice to urban parks? 2) How the physical attributes of network systems impact route directness and choice to urban parks? 3) Do Abu Dhabi's public realm planning and design guidelines provide effective polices with regard to accessing parks *via* efficient connected routes? And how the outcome of this research can enhance planning policies that address different network typologies to ensure better access to parks.

2 Literature review

2.1 How the pandemic changed daily activities

Extraordinary regulations have been mandated to curb infection rates during the recent COVID-19 pandemic resulting in limited movement, travel, activity participation and mobility choices worldwide (De Vos, 2020). Governments resorted to extreme measures in order to prevent the airborne Corona virus transmission; this included enforcing social distancing, lockdown of public indoor spaces, and home-confinement, which cumulatively impacted people's mental and physical health (Armbruster and Klotzbucher, 2020; Bustamante et al., 2022). Daily lifestyle habits, therefore, have been disturbed and typical daily activities, such as physical travel to school and work, were replaced by online ones (Mouratidis and Papagiannakis, 2021). This resulted in drastic changes to urban mobility in terms of travel frequency, mode choice, and distance. For example, different countries implemented distance-based mobility restrictions that confined people's movement to their neighborhoods (Glavan et al., 2022). In France, in Spring 2020, movement from each household was restricted to be within a 2-km distance (Kakderi et al., 2021), while in Australia, the distance was bound to a 5-km radius from each household (Reuters, 2021). In terms of travel mode choice, social distancing constraints disturbed public transportation services causing them to be either halted or restricted in capacity (Kamga and Eickemeyer, 2021; Basu and Ferreira, 2021); as a result, their use rates dropped significantly (Hu et al., 2021).

Mobility preferences shifted towards active modes of travel such as walking and cycling (Nikiforiadis et al., 2022). A key study by Hunter et al. (2021) of 10 metropolitan areas in the United States reported significant insights about walking behavior before, during, and after the pandemic. Their data indicated that 75.45% of pre-pandemic walking was utilitarian with an average daily distance of 432.78 m while recreational walking, although lower in frequency, was longer in terms of daily average distance at 1495.24 m. Their evaluation of walking during the pandemic indicated a reduction in utilitarian walking frequency by 39.2%, a trend that has persisted even after the ease of lockdown measure. On the other hand, recreational walking demonstrated an increase in distance and frequency, exceeding utilitarian walking in many cases. Active travel, walking and cycling, was observed to become a primary source of mobility in many cities during the pandemic (Barbarossa, 2020; Nikiforiadis et al., 2022); this motivated local municipalities, such as in London and Mexico City, to improving or adding new cycling lanes and widening sidewalks to accommodate increased pedestrian flows while maintaining social distancing (Frangoul, 2020; Shaping Pots-Covid Mobility in Cities, 2023).

Mouratidis and Papagiannakis (2021) acknowledged that walking and cycling were recognized as safe mobility option during the pandemic. Their study also indicated that "Green spaces were considered to be increasingly important during COVID-19 as they provided space for performing leisure activities with a lower risk of infection" (Mouratidis and Papagiannakis, 2021, p.3), thus "helped mitigate the negative implications of COVID-19 for quality of life" (Mouratidis and Papagiannakis, 2021, p.4). Green spaces, therefore, emerged as sanctuaries and gained increased significance. Living within a close proximity to green spaces has motivated many city dwellers to relocate to suburbs; a phenomenon that was observed in North American cities such as Boston, New York, Los Angeles, Toronto (Saunders, 2020; Ramani and Bloom, 2021), and in other parts of the world including London (The Guardian, 2020), Stockholm (Vogiazides and Kawalerowicz, 2022), as well as Spain (González-Leonardo et al., 2021). These new urban living dynamics positioned the suburbs as an attractive alternative to inner-cities, they also re-prioritized parks as an indispensable attribute of post-pandemic living (Frumkin, 2021; Mouratidis and Papagiannakis, 2021). Central to the debate on post-pandemic approaches to planning policies and practices is the work on "enhancing public spaces and on the rethinking of roads to promote walking and cycling" (Barbarossa, 2020, p.12).

2.2 Connectivity to parks

Urban green spaces, including parks, are recognized as an integral part of the built environment (Pfieffer and Cloutier, 2016); this is because they contribute towards the wellbeing of the residents by providing recreational activities (Larson et al., 2016) and by improving the livability of neighborhoods (Baur and Tynon, 2010). Their impact on reducing levels of stress and fatigue, on residents, have also been established in the literature prior to the pandemic (Wood et al., 2017; Sugiyama et al., 2018). Geng et al. (2020) analyzed parks visitation trends, during the pandemic, in over 90 countries and found that parks received more visits since the spread of COVID-19. This was attributed to the role of parks in mitigating the negative implications of the pandemic over the residents' mental and physical health. A study by Ugolini et al. (2020) revealed that the rate of people, in Italy, who opted for parks at distances less than 200 m slightly increased (no more than 10%) and visits to parks at a farther distance (more than 500 m) slightly decreased (by 9% on average). The study also indicated that walking was the primary mode of mobility towards parks, and farther away parks "were probably appreciated by some respondents precisely for the opportunity they offer to do more physical exercise" (p.8). Access to Parks is often evaluated in terms of distance, Euclidean or network-based, as well as the count, total area, or density of parks (Zhang et al., 2011; Nicholls, 2001). Other studies analyzed the routes to parks which provides a more comprehensive approach in understanding the physical environment around parks (Zhou and Xu, 2020; Dills et al., 2012). Lee (2019) expanded this notion by introducing a methodology to evaluate the urban morphological context of parks using urban form variables, such as parcel and block size, plot density, building setbacks, and street intersections, to name a few.

Cities of the Arabian-Gulf have also been subject to mobility restrictions during the COVID-19 pandemic, and the earlier discussed implications were also observed in the Gulf region (Cheikh Ismail et al., 2020). The restricted movement implications were further amplified by the challenging hot weather especially with other public places, such as shopping malls, being under lockdown. This research explores the efficiency of routes connecting residents with their local neighborhood parks in Abu-Dhabi. The urban system of Abu Dhabi has implemented aggregates of superblocks, in the form of low-density suburbs, during its urbanization process which started back in 1970s (Elsheshtawy, 2008). Similar urban expansion strategies are also observed in other GCC cities (Choguill, 2008). The urban expansion started initially at Abu Dhabi Island and grew gradually towards the mainland. Prior to 1990s, neighborhoods were designed with reasonable densities, integrated street systems with alleyways to accommodate pedestrians, and grided street systems with mixed land-uses towards the edges. After 1990s, neighborhoods street typologies became fragmented with looping or curvilinear streets, residential densities decreased, and service centers accounting non-residential land-uses were housed in centralized locations (Bani Hashim, 2016). In terms of parks provision in the city, Department of Transport and Municipalities (DMT) manages 531 ha of developed parks that serves a total population of almost one million (0.54 ha per 1,000 resident). The Abu Dhabi Island has 386 ha of parks (0.67 per 1,000 residents), while the mainland, predominantly suburban areas, has 145 ha of parks (0.36 ha per 1,000 residents) (Abu Dhabi Urban Planning Council, 2011). These values are well below the adopted planning guidelines in most countries; the American Planning Association standards for recreational areas, for example, mandates a minimum of 4 ha per 1,000 residents (Leonard and Egan, 2014). With the population of the city is projected to grow by 2030, the DMT is planning to increase parks area to 1.3 ha/1,000 resident (Abu Dhabi Urban Planning Council, 2011).

2.3 Measuring connectivity to parks

Jabareen and Eizenberg (2021), in illustrating aspects of current urban forms failure during the pandemic, explained that "the common allocation of parks and open spaces, ranging from the metropolitan-scale park to the neighbourhood park, was insufficient in providing residents under restricted-movement orders the open space they needed." (p.5). On this vein, this research seeks to understand how the current urban context of Abu Dhabi's neighborhoods impacts route connectivity, in terms of directness/shortest travel distance and redundancy/multiple routes to the park. Leslie et al. (2007) explained that the degree at which a neighborhood is walkable refers to "the extent to which

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characteristics of the built environment and land use may or may not be conducive to residents in the area walking for either leisure, exercise or recreation, to access services, or to travel to work." (p.113). Therefore, mobility decisions are found to be sensitive or highly impacted by the physical attributes of urban form (Porta and Renne, 2005; Lee and Moudon, 2008; Frank and Engelke, 2005). Gori et al. (2014) study highlighted the association between active transportation, walking and cycling, and the availability of a pedestrian friendly street network: "Increased distances and poor connectivity usually discourage walking and bicycling and, consequently, physical activity" (p.38). Other studies have also emphasized on street connectivity correlation with walkability (Saelens et al., 2003; Porta and Renne, 2005). Larranaga and Cybis (2014) describe how the street pattern (grid-like, curvilinear, etc.), the nature of intersections, and their density and frequency at smaller distances, are used as indicators of pedestrian-friendly urban settings.

This article adopts Network Connectivity, which is conceptually concerned with evaluating distances and availability of sufficient pedestrian routes, to evaluate the efficiency of current street systems with regard to extended walking distances towards parks, that are up to 1-Km away from residents. This is because common walking distance threshold are at 15–20-min walk, at a moderate peace, which corresponds to approximately a 1-Km distance (Stessens et al., 2017; Nicholls, 2001). Some studies suggest that people are less likely to visit parks that are beyond this distance threshold (Toftager et al., 2011). Networks with higher values of: intersection density (Reilly and Landis, 2010), street density (Handy, 1996), intersection ratio (Peponis et al., 2007), and link-node ratio (Ewing, 1997), are regarded as more connected for ensuring better route connectivity between origins and destinations. Those metrics, despite being favored for ease of calculation, fail to capture the interplay among the multiplicity of other variables and fail in capturing the impact of the network's pattern (Peponis et al., 2008). Additionally, when planning standards have implemented them as numerical benchmarks, they proved to be susceptible to "gamification" (Guinn and Stangl, 2014). Other connectivity metrics that measure the size and configuration of blocks in terms of their density (Cervero and Radisch, 1996), perimeter (Song and Knaap, 2004), area (Hess et al., 1999), or mean length (Cervero and Kockelman, 1997) have also proved to conceal obstructing configurations of blocks that impedes travel at shorter distances despite meeting the planning standards benchmarks (Guinn and Stangl, 2014). Because distance is a detrimental factor in active travel, many studies suggest that "the concept of street connectivity for walking can be better captured with distance measures between home and particular activities important for walking, than broadly with variables such as average block size or intersection density" (Lee and Moudon, 2008, p.214). Therefore, three distance-base measures: Pedestrian Route Directness, Redundant Routes Count and Route Redundancy Index, are selected to evaluate network connectivity. Because street systems are only one aspect of the urban form, other physical attributes are also quantified and used in explaining the analyses results. Those attributes include: network and intersection density, distance between intersections, percentages of arterials/ collectors in the network, average block size, percentages of 4-way intersections, and average distance to the park. The complementary role these attributes play in defining urban spatial systems is highlighted in Southworth's (2005) description of a walkable city, where he explains that actual walking requires fine grained patterns and interconnected continuous routes to minimize distances, thus a topology of "a high density of intersections and small block size" results in a "high degree of connectivity" (Southworth, 2005, p.250). Additionally, studies like Marshall et al. (2014) and Winters et al. (2010) have emphasized the combined effect of considering the network structure, in terms of percentages of collector, arterials and local streets, alongside other attributes when evaluating active mobility.

3 Methodology

3.1 Selection of samples

To evaluate connectivity to green spaces, 16 residential neighborhood parks, within superblocks, have been chosen (Figure 1). The selected samples are grouped into six different typologies and accounts for diversity in networks typologies, residential densities and parks' locations within the superblocks. Additionally, the selected samples represent different planning phases and are strategically scattered across the city, including its more established central districts in the Island as well as its newer outlying developments. Wheeler (2015) indicated that streets' patterns are among the most key deterministic physical features of the urban form that significantly shape walking behaviors. Therefore, the selected samples are categorized into six main groups based on the street's typology/pattern. The groups are: grid-iron, semi-grid, semi-grid with a service spine, semi-grid with a service core, interlocked with a core and two additional samples with hybrid patterns of a compartmentalized semi-grid, and another with a diagonal semi-grid and a service core (Figure 2). Connectivity is evaluated for the network captured within the park's service area, of a 1-km network-based distance, in two scenarios: streets only, and a combined network of alleyways and streets. This offers a realistic prediction of the contribution of pedestrian-only routes/alleyways in improving access to local parks at shorter distances. Therefore, samples' attributes with regard to: network and intersection density, percentages of 4-way intersections, average distance between intersections, average distance to parks, percentages of arterial/ collectors, and average block size are evaluated individually, per sample, for both network scenarios, streets only (Table 1) and streets and alleyways (Table 2), in order to evaluate their impact on the network connectivity.

Aerial photos and GIS information were provided from Abu Dhabi Department of Municipalities and Transport (DMT). The provided GIS data is used to identify the parks' centroids in each superblock, and consequently the network-based service area within a 1 km, is generated. All the residential plots that have a shortest route to the local park, within that distance threshold, are captured with this service area (Gori et al., 2014). Most studies adopted a maximum walking distance of 1 km to assess connectivity to local playgrounds and parks (Van Herzel and Wiedemann, 2003; Tsou et al., 2005). The parks' entrances are also identified to ensure the analysis accuracy in terms of simulating actual traveled routes from residential plots to the local park. Therefore, residential plots, located within the 1 km service area, are used as origins for trips to each of the park's entrances, that are deemed as destinations.

FIGURE 1
Satellite images of the selected samples showing superblock's boundaries (Esri, 2022).

3.2 Network analysis metrics

Pedestrian connectivity evaluates the directness of available routes between pairs of locations at shortest distances (Randall and Baetz, 2001). This concept is mainly concerned with the spatial structure of the street network (Porta and Renne, 2005) and how its attributes are detrimental to pedestrian trips in terms of frequency and distribution (Ozbil et al., 2011). However, when pedestrian travel is examined, it is found that deviations from the shortest routes are common (Basu and Sevtsuk, 2022). While alternative route choice is impacted by a multitude of variables, such as path comfort and safety, distance is usually found to be the most critical to be minimized by pedestrians (Sevtsuk and Kalvo, 2022). Additionally, the count and type of intersections, or turns, are found to impact route choice (Hillier and Iida, 2005; Lue and Miller, 2019). Therefore, connectivity is used to characterize streets networks in terms of two aspects: the first is whether routes can ensure connectivity to destinations at shorter distances, and the second is the availability of a multitude of routes/route redundancy, with a minimum deviation from the absolute possible shortest route connecting an origin with a destination. Tal and Handy (2012) offered a definition of connectivity that accounts for both aspects, route directness and route redundancy, by explaining that connectivity is "a measure of the quantity of the connections in the network and thus the directness and multiplicity of routes through the network" (p.48). Therefore, three metrics are used to evaluate streets' network connectivity in the selected samples: the Pedestrian Route Directness (PRD), the Redundancy Index (RI), and the Redundancy Count (RC). The former evaluates how direct the routes are and the two later ones describe the diversity of available alternative routes that are within a minimum distance deviation from the shortest route.

3.3 Pedestrian route directness

The first metric used to quantify the network connectivity is the Pedestrian Rout Directness (PRD) (Stangl, 2012). The Pedestrian Route Directness metric is favored over other connectivity measures for being distance-based, and for providing intuitive results (Guinn and Stangl, 2014). PRD is calculated as the ratio of the network distance between an origin and destination to the Euclidean distance or to the straight-line distance separating those points. The resulting value is used to evaluate how direct or efficient a route is; values closer to one are deemed as the most efficient. Utilizing the attained GIS data, the identified residential plots' centroids, that lie within the 1-Km service area of the local park in each sample, are treated as origins and the parks' entrances as destinations. The PRD value is

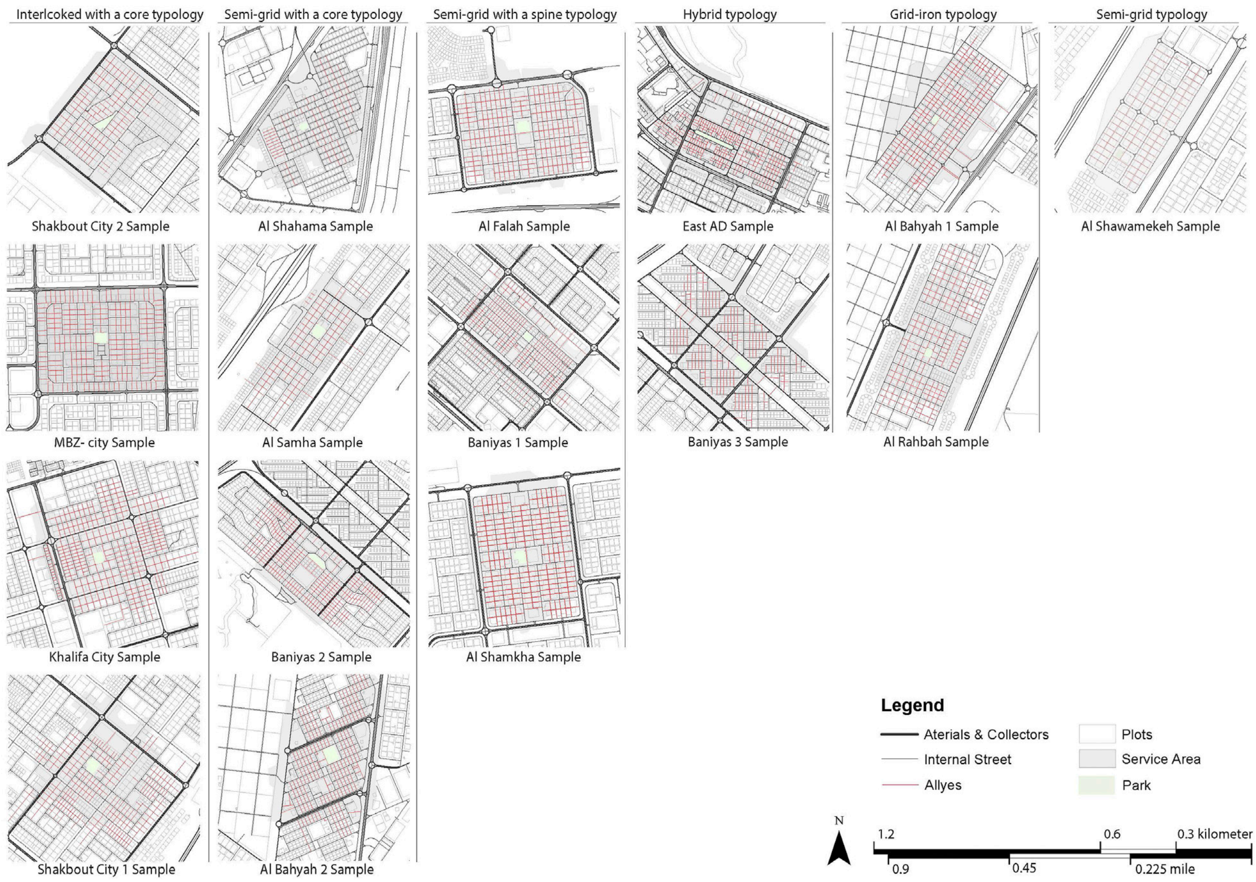

FIGURE 2
Selected samples showing parks' locations and the 1-km distance based service area.

calculated for trips generated from each origin, a residential plot captured by the service area, to each park's entrances, and then averaged per residential plot. Previous studies of street connectivity have shown that for suburban developments, the typical PRD threshold value is between 1.5 and 1.6 (Hess, 1997; Hess et al., 1999; Randall and Baetz, 2001). Additionally, Abu Dhabi's sustainability rating framework "Estidmama" has adopted 1.5 as a threshold when evaluating street connectivity. Therefore, the same value of 1.5, which indicates that the shortest routes are at maximum 50% longer than the Euclidean distance, is used to benchmark the average PRD value of each sample as passing or failing. PRD values are averaged within each sample and the sample's average PRD value is used an indicative of its route directness. Samples with an average PRD value lower than 1.5 are deemed as passing, suggesting that most of residential plots in that sample are connected to the local park with efficient routes.

3.4 Network route diversity: Redundancy index and count

Two metrics are used to quantify the availability of alternative routes, Redundancy Index (RI) and Redundancy Count (RC). Ozbil et al. (2011) study indicated that network connectivity can be described using a multitude of measures, including route choice which can be explained as "how many shortest paths between all possible paired origins and destinations go through each space." (p.126). This emphasizes two aspects. First: an expanded understanding of connectivity as addressing both distance and route choice. Second: the presence of multiple alternative routes that can be traversed with minimum deviation from the shortest route is an indicative of a more connected network. Similar to route directness, the pedestrian route choice measures, Redundancy Index and Count, are impacted by different attributes that can be either qualitative such as the sidewalk availability and continuity (Broach and Dill, 2016), or quantitative such as land use (Borst et al., 2009), or density and building heights (Guo, 2009; Hahm et al., 2017). The focus of this study is the quantitative attributes of street network, in terms of distance, network density, intersections and layout, in providing efficient multiple routes to parks. To ensure that alternative routes have reasonable deviation from the shortest route distance of no more than 20%, a value of 1.2 for the Detour Ratio is used, which is a factor that controls the maximum allowed deviations in distance from the shortest route (Sevtsuk and Mekonnen, 2012). This is with regard to the hot-arid climate of Abu-Dhabi and the fact that in such climate, pedestrians, when considering alternative routes, opt for shorter distances. For each residential plot, the count of alternative routes connecting them

TABLE 1 Quantified physical attributes for the streets only network scenario.

Network scenario	Typology	Sample's name	Sample's area	Arterials/ Collectors percentage	Network density	Intersections density (intersection/Ha)	4-Way intersection percentage	Average block size (Ha)	Average distance to park (Km)	Average between intersections (Km)
Streets Only	Grid Iron	Al Bahya	138.11	26.82	0.13	0.28	0.08	5.21	0.57	229.00
		Al Rahbah	111.20	0.00	0.11	0.30	0.08	5.38	0.57	200.00
	Semi-grid	Al Shawamekeh	57.30	0.00	0.16	0.80	0.00	6.03	0.47	219.00
	Semi-grid with spine	Al Falah	129.04	0.00	0.17	0.37	0.01	6.62	0.59	277.00
		Baniyas	117.04	27.59	0.23	0.55	0.04	2.53	0.61	261.00
		Al Shamkha	148.30	56.77	0.17	0.23	0.00	6.75	0.61	240.00
	Semi-grid with a core	Al Shahama	133.20	0.00	0.29	1.95	0.19	2.11	0.65	217.00
		Al Samha	79.70	10.00	0.14	0.31	0.03	6.26	0.74	274.00
		Baniyas-2	112.40	52.57	0.18	0.52	0.02	4.13	0.60	243.00
		Al Bahya-2	99.40	51.90	0.20	1.00	0.05	2.21	0.64	145.00
	Interlocked with a core	Shakbout-2	129.45	0.00	0.14	0.54	0.00	7.17	0.79	284.00
		MBZ	134.00	0.00	0.12	0.48	0.01	5.63	0.62	265.00
		Khalifa City	120.36	55.01	0.14	0.35	0.03	7.07	0.69	254.00
		Shakbout City	129.60	42.70	0.15	0.40	0.04	7.14	0.66	345.00
	Hybrid	East AD	104.80	32.00	0.28	2.63	0.07	1.77	0.67	100.65
		Baniyas-3	133.39	41.58	0.20	1.05	0.02	2.36	0.69	182.00

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TABLE 2 Quantified physical attributes for the streets and alleyways network scenario.

Network scenario	Typology	Sample's name	Sample's area	Arterials/ Collectors percentage	Network density	Intersections density (intersection/Ha)	4-Way intersection percentage	Average block size (Ha)	Average distance to park (Km)	Average between intersections (Km)
Streets and Alleyways	Grid-iron	Al Bahya	138.11	17.47	0.26	2.80	24.03	0.51	0.58	56.00
		Al Rahbah	111.20	12.30	0.30	2.73	41.12	0.59	0.58	77.50
	Semi-grid	Al Shawamekeh	57.30	13.32	0.30	3.37	22.28	0.57	0.45	50.00
	Semi-grid with spine	Al Falah	129.04	35.84	0.27	2.36	45.07	0.59	0.57	66.00
		Baniyas	117.04	15.87	0.29	2.44	67.72	0.58	0.60	63.50
		Al Shamkha	148.30	29.87	0.32	2.35	35.53	0.60	0.59	69.00
	Semi-grid with a core	Al Shahama	133.20	20.71	0.36	1.99	22.64	0.65	0.55	79.00
		Al Samha	79.70	26.61	0.28	1.91	38.16	0.56	0.57	71.00
		Baniyas-2	112.40	26.24	0.65	3.74	36.19	0.38	0.63	53.00
		Al Bahya-2	99.40	28.07	0.30	1.91	34.74	0.33	0.57	56.00
	Interlocked with a core	Shakbout-2	129.45	12.09	0.32	3.05	19.24	1.10	0.71	47.00
		MBZ	134.00	26.21	0.30	3.26	14.87	0.45	0.63	58.00
		Khalifa City	120.36	28.05	0.37	3.19	42.97	0.39	0.58	60.00
		Shakbout City	129.60	17.49	0.36	3.01	23.08	0.61	0.60	59.00
	Hybrid	East AD	104.80	16.15	0.18	5.18	16.94	0.72	0.50	86.66
		Baniyas-3	133.39	26.11	0.30	2.56	27.78	0.42	0.70	50.00

TABLE 3 Connectivity analyses results for the two network scenarios.

Typology	Sample's name	Sample's average pedestrian route directness (PRD)		Sample's average route redundancy index (RI)		Sample's median route redundancy count (RC)	
		Streets only	Streets and alleyways	Streets only	Streets and alleyways	Streets only	Streets and alleyways
Grid Iron	Al Bahya	1.36	1.29	1.68	3.52	1.00	30.00
	Al Rahbah	1.40	1.34	1.49	4.61	2.00	39.00
Semi-grid	Al Shawamekeh	1.44	1.24	1.47	3.52	12.00	9.00
Semi-grid with a spine	Al Falah	1.42	1.30	2.65	4.47	1.00	27.00
	Baniyas	1.42	1.30	1.70	4.73	1.00	24.00
	Al Shamkha	1.49	1.33	1.38	4.48	1.00	26.00
Semi-grid with a core	Al Shahama	1.51	1.35	2.29	3.94	4.00	18.00
	Al Samha	1.90	1.36	1.41	3.74	1.00	12.00
	Baniyas-2	1.43	1.37	2.00	5.86	2.00	29.00
	Al Bahya 2	1.76	1.62	2.00	4.63	2.00	20.00
Interlocked with a core	Shakbout 2	1.59	1.38	1.61	3.32	3.00	18.00
	MBZ	1.50	1.37	1.89	4.77	5.00	25.00
	Khalifa City	2.00	1.41	1.51	3.00	3.00	18.00
	Shakbout City	1.64	1.40	1.32	3.32	1.00	26.00
Hybrid	East AD	1.95	1.47	3.21	3.51	19.00	112.00
	Baniyas-3	1.96	1.58	2.14	3.60	2.00	29.00

with each of the local park's entrances, providing that they are 20% at most longer than the absolute shortest route, is calculated and averaged. However, unlike the case with the PRD value, the median is used to represent the sample's Redundancy Count instead of the average. This is because the median value was found to be a better representative of the generated analysis results, considering the large disparities in the count of redundant routes between plots. The Redundancy Index refers to the ratio between the sum of the network length of all the alternative routes to the shortest path's length connecting the same pair of nodes (Sevtsuk and Mekonnen, 2012). Redundancy Index enables the determination of how much more network distance can be traversed *via* alternative routes that are at most 20% longer than the shortest route, thus offering the opportunity for more parts of the urban setting to be visited (Sevtsuk and Kalvo, 2022). As with the PRD index, the Redundancy Index is calculated from residential plots centroids to each of the park's entrances and averaged. The average of those values is then used to represent the sample's Redundancy Index. Values closer to 1 indicate either no route diversity or that the available alternative routes exceed the shortest route length by more than 20%; values larger than 1 indicate route diversity. Therefore, the value of 1 has been selected as a benchmark of determining if a residential plot has route redundancy when traveling towards local parks, at reasonable distances.

4 Results

Results of the network connectivity for both network scenarios, in terms of route directness (PRD), Count of Redundant Routes (RC), and Route Diversity Index (RI) are summarized in Table 3. The impact of urban form on connectivity to local parks, whether for strolling or towards the park itself as a destination, has been explored by quantifying the physical features of the network system. It is found that connectivity levels are impacted by both the typology, in terms of how streets and blocks are configured, and by the individual characteristics observed in each sample, such as percentages of arterials/collectors found in the sample's network, densities of the network and intersection, and the average block size. Alleyways are also found to improve connectivity significantly; this is due to their impact in reducing travelled distances to local parks. The inclusion of alleyways increases the typology griddness by supplementing the network with redundant shorter routes, increasing intersections, and reducing the average block sizes. The count of redundant routes is impacted by the typology in terms of intersection density. Redundancy Index is found to provide insights about the efficiency of alternative routes, in terms of distance. When, for example, two samples have equal counts of alternative routes and average distances to parks, the sample with the lower RI index indicate more efficient redundant routes.

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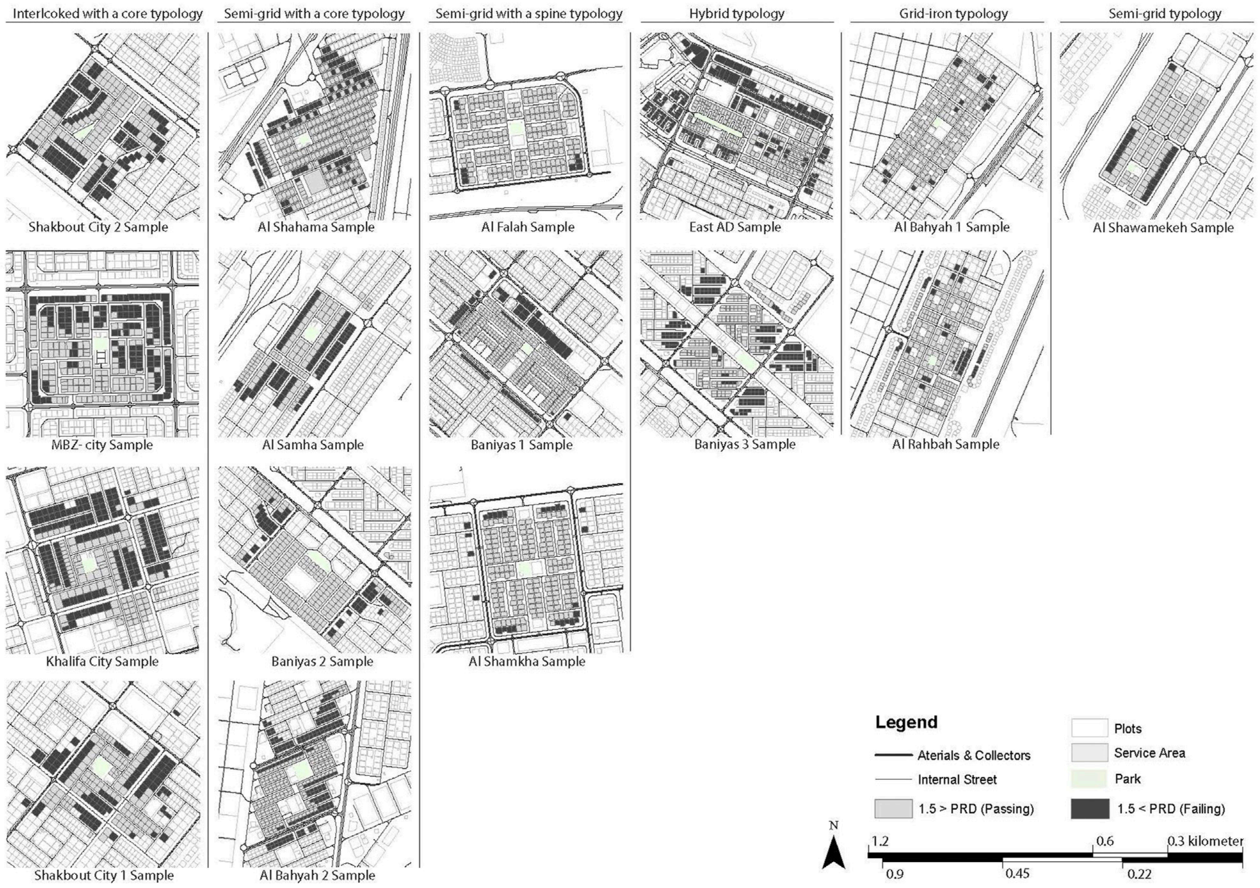

FIGURE 3
Samples showing Pedestrian Route Directness (PRD) analyses results for the streets network.

4.1 Network scenario: Streets

Connectivity results for the streets only network scenario are depicted in (Figure 3), which indicates the passing and failing plots in each sample in terms of the PRD measure, in (Figure 4) which indicates the plots with route redundancy in each sample in terms of the RI measure. Samples with a grid-iron topology, Al-Bahya and Al-Rahba, are found to have the lowest average PRD value at 1.36 and 1.40 respectively. This is intuitively attributed to their gridded layout which results in shorter average distances to local parks at (0.57 km). However, in terms of the availability of redundant routes, RC values indicate that most of the residential plots has a median of 2 route choices to the park, and RI values indicate that their combined lengths are almost 1.5 times longer than the shortest rout's distance. Since redundant routes in this analysis are bound to 20% deviation at most from the shortest route's length, such results suggest that more redundant routes may exist but with larger distance deviations. This is attributed to the low network and intersection densities in Al-Bahya and Al-Rahba. The next efficient typology, in terms of route directness, is the semi-grid found in Al-Shawamekh. The average PRD value of this sample is at 1.44, below the test threshold. Shortest routes of some plots, in this sample, traverse longer block faces resulting in an overall higher average PRD than the previously mentioned samples, despite having lower average travel distance to parks at (0.47 km). RC value indicate the availability of a median of 12 routes per residential plots, with a minimum deviation from the shortest distance (RI = 1.47), suggesting that such routes are efficient in terms of distance. The relatively high median RC value is attributed to the middle blocks' configuration, which provide the possibility of adjacent plots to access the park by traversing their relatively short faces. Another efficient typology is the semi-grid with a central service spine; three samples belong to this typology group: Al-Falah, Baniyas, and Al-Shamkha, all with average PRD values below the test threshold. This is attributed to the location of the parks within the central spine, thus routes leading to parks can be traversed at almost equal distances from all directions. The average shortest route distance in those samples is relatively low (around 0.60 km). Route diversity, however, in this typology is impacted by the frequent T-type intersections which reduces the count of available redundant routes. Therefore, the median RC value for those samples is one, suggesting that the majority of plots are connected with only one efficient route to the park.

Less efficient typologies have a service core with either a street pattern of semi-grid or with an interlocked pattern. The former typology includes four samples: Al-Samha, Al-Shahama, Al-Bahya-2, and Baniyas-2. Except for Baniyas-2, all of other samples have an average PRD value above 1.5. The low route

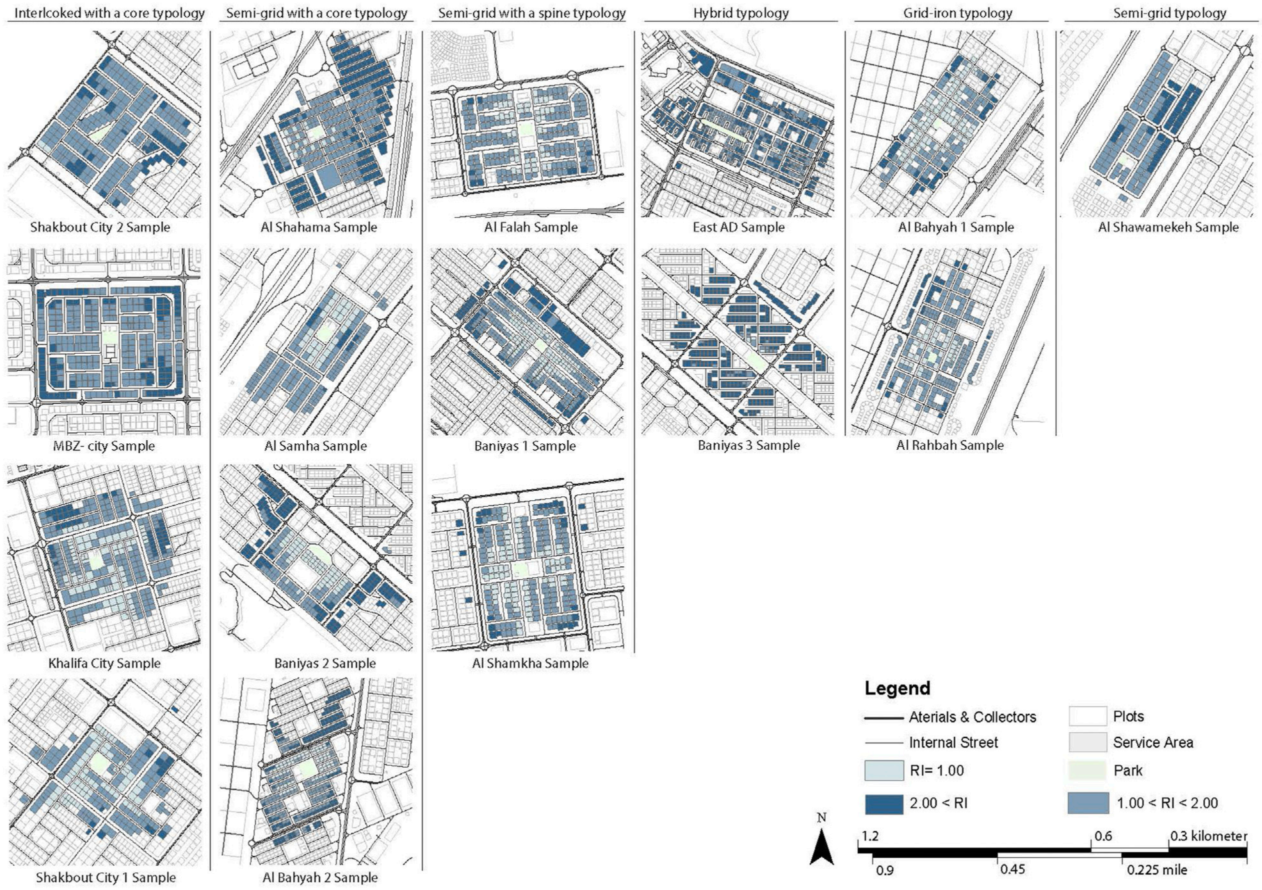

FIGURE 4
Samples showing Route Redundancy Index (RI) analyses results for the streets network.

directness values in Al-Samha and Al-Shahama (PRD = 1.90, and 1.50 respectively) are attributed to the block's configuration and face length (exceeding 0.65 km). The longitudinal blocks, in both samples are resulting in longer average shortest routes towards the local park (at 0.74 and 0.65 km) respectively. For Al-Bahya-2, the low average PRD value (PRD = 1.76) is attributed to the street's hierarchies included in its network, where 51.90% of it are arterials/collectors which impede route directness. Baniyas-2 has similar network composition in terms of arterials/collectors, but its average PRD value is at 1.43, suggesting significantly better route directness than Al-Bahya-2. This is attributed to its block configuration which alternate in direction, thus allow for the shorter rather than longer block faces to be traversed. This illustrates the extent to which the typology impact network efficiency. Both of Baniyas-2 and Al-Bahya-2 samples have a median of 2 redundant routes per residential plots, the RI value is also at 2 for both, suggesting a rather high cumulative distance deviation from the shortest route. Al-Shahama median RC value indicates higher count of redundant routes at 4 per residential plot, and the RI value at 2.29 suggests that those alternative routes are relatively efficient distance-wise. This is mainly attributed to Al-Shahama having the highest intersection density, among the typology samples, and the lowest average block size.

The other less efficient typology is the interlocked block configuration with a service core. It includes four samples: Khalifa-city, MBZ-city, Shakbout-city-1 and Shakhbout-city-2. The typology's street patterns, and block configurations result in longer block faces and T-type intersection. Therefore, routes traversed to reach the nearest intersection tend to be longer on average. This is evident from having longer shortest routes to the local parks on average, when compared with samples of other typologies. MBZ-city is the only sample in this typology with an average PRD value of 1.5 which meets the directness threshold. Unlike other samples in this typology, MBZ has an average block size lower than 7.0 ha and a service area that includes local streets only. Conversely, Khalifa-city and Shakhbout-city-1 samples have larger block sizes on average (7.0 ha or higher) and a service area that includes arterials and collectors (percentages of arterials/collectors in both samples are 55% and 42% respectively) which compromises route continuity. As a result, the average PRD values of those samples are above 1.5. Shakhbout-city-2 sample, although it includes local streets only, it is route directness is impacted by the large average block size at 7.17 ha, resulting in an average PRD value above the test threshold. In terms of route redundancy count for samples belonging to this typology group, the lack of sufficient intersection densities is

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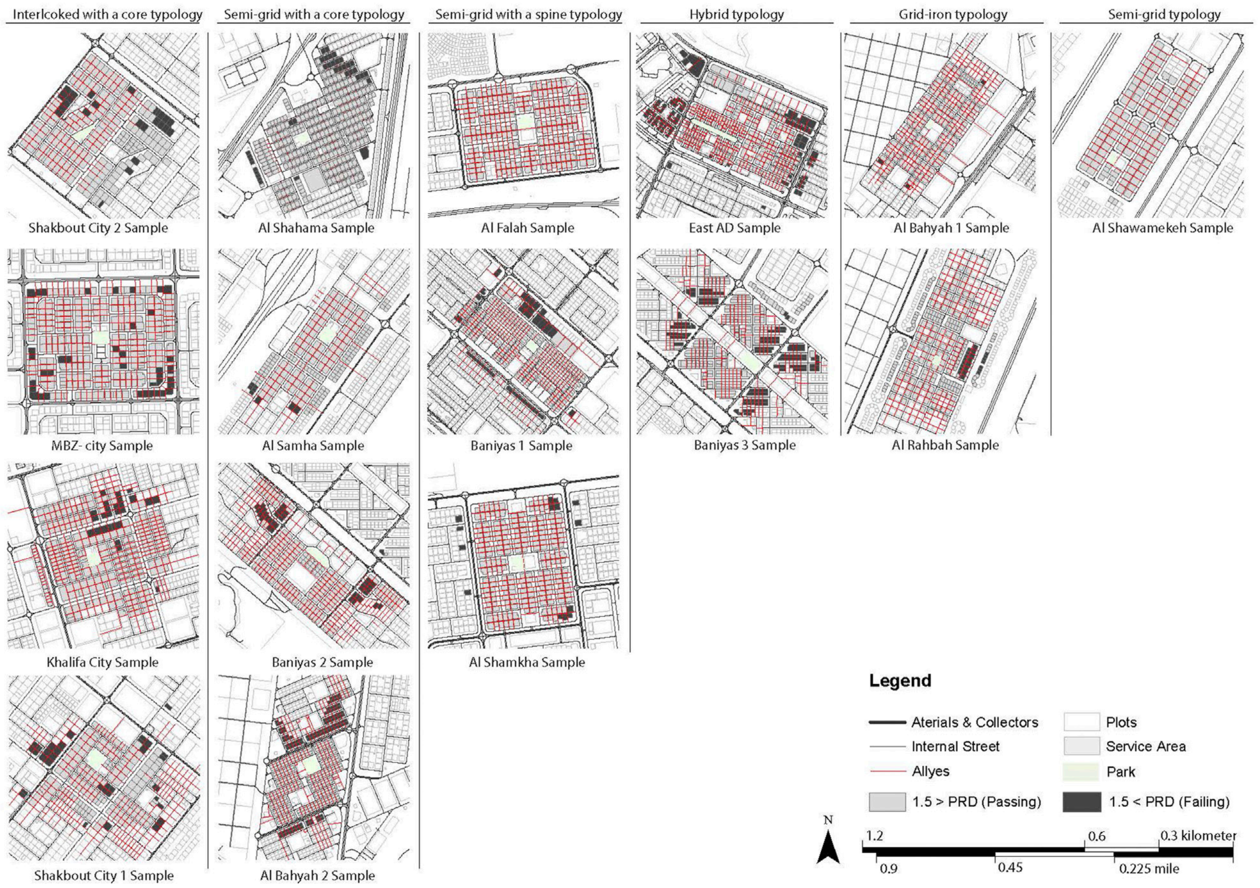

FIGURE 5
Samples showing Pedestrian Route Directness (PRD) analyses results for the streets and alleyways network.

significantly impacting the availability of redundant routes, resulting in median RC values of 5 or lower for those samples. However, RI values (between 1.32 and 1.89) indicate that for the few plots that have alternative routes, their cumulative lengths are within minimum deviation from the shortest routes, or 1.89 longer than the shortest route at most.

Two additional samples are considered to have inefficient typologies. The East-AD sample with its hybrid typology of semi-grid and T-type intersections, which is also internally divided into compartments by collectors. Despite having the highest intersection density and the lowest average block size, its average PRD value is at 1.95, suggesting very low network efficiency. This is attributed to the impeded route continuity due to the heterogeneous street pattern, within the sample, and the inclusion of arterials/collectors (at 32% of the total network length). However, the typology provides a median of 19 redundant routes to parks, the highest among the studied samples, with total distances expanding to almost 3 times the shortest route length. The other sample is Baniyas-3 with a diagonal semi-gird street pattern and a central spine. The average PRD value of this sample is above the test threshold at 1.96, suggesting an inefficient network. Distances to the local park is less direct due to the diagonal street pattern; this also impacts the availability of redundant routes to a median of (RC = 2) per residential plot.

4.2 Network scenario: Streets and alleyways

Connectivity results for the streets and alleways network scenario are depicted in (Figure 5), which indicates the passing and failing plots in each sample in terms of the PRD measure, in (Figure 6) which indicates the plots with route redundancy in each sample in terms of the RI measure. For most samples, the inclusion of alleyways improves network connectivity in terms of route directness and route redundancy. Alleyways are found to reduce the average shortest route distances, the spacing between frequent intersections, and the average block size. Their greater impact is found to be in increasing the networks densities and intersections, resulting in significantly higher count of redundant routes. The improved average PRD values are attributed therefore to the improved route continuity since routes to parks can be navigated *via* alleyways at shorter distances (Figure 7). In this network scenario, Al-Shawamekh typology is converted from a semi-grid typology into a gridded one, and it is reporting the lowest average PRD value at 1.24, suggesting a highly efficient network in terms of route directness. RC median value is at 9 redundant routes, per residential plot, and the RI value is at 3.52. The count of redundant routes, however, has dropped from a median of 12 to 9; this is attributed to the fact that alleyways have replaced street segments found in shortest routes, which resulted in relatively shorter routes

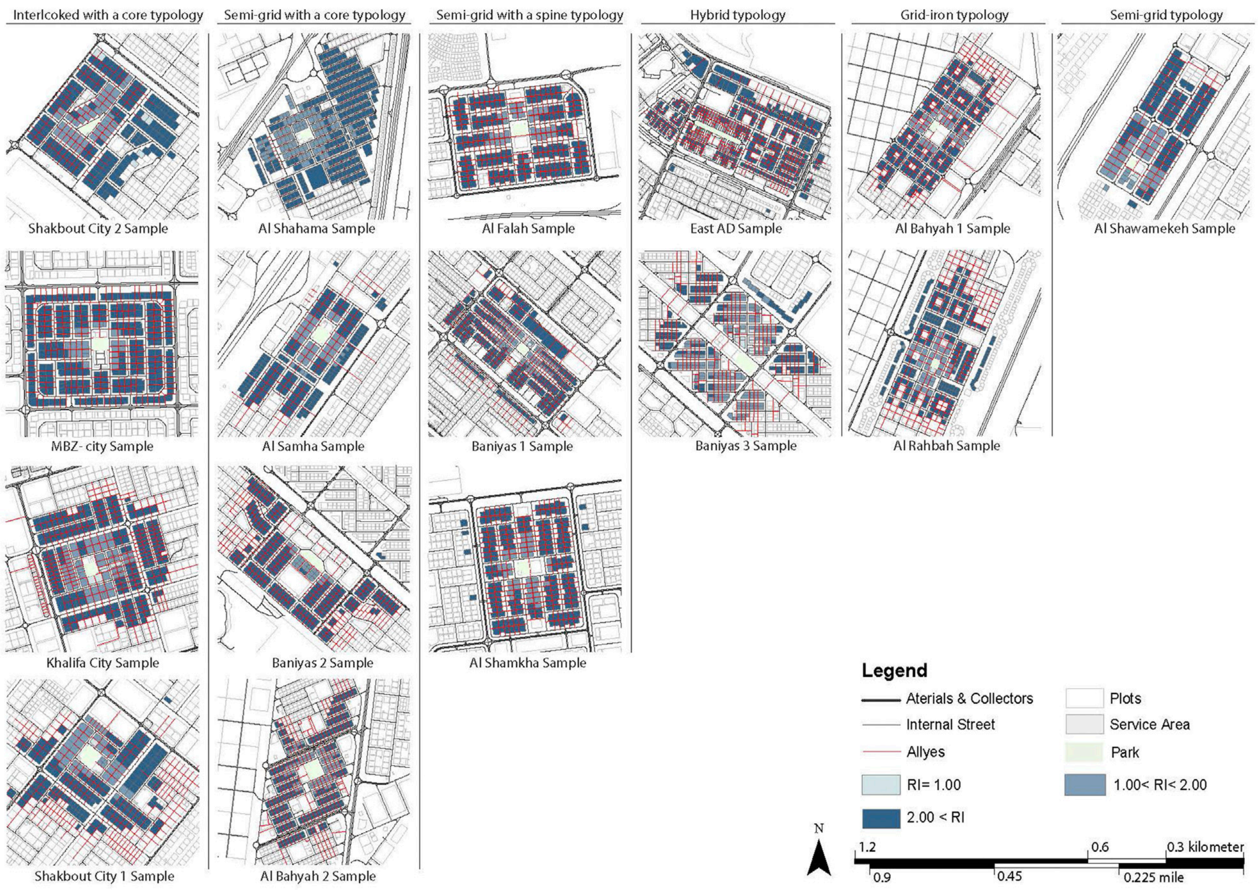

FIGURE 6
Samples showing Route Redundancy Index (RI) analyses results for the streets and alleyways network.

and have, therefore, reduced the allowed distance deviation. Samples belonging to the grid-iron typology, Al-Rahba and Al-Bahya, have also reported an improved average PRD values below 1.35. This is because alleyways increased the networks density. The increased intersection density and the reduced spacing between frequent regular intersections are contributing to those samples having the highest reported median count of redundant routes at (30 for Al-Rahba and 39 for Al-Bahya), with an RI values of 3.52 and 4.61 respectively. An abundance of alternative routes exists with total lengths that expands 4.6 times at most, suggesting that most of these routes have an acceptable deviation from the shortest route.

The typology group with the semi-grid and a spine, which includes: Al-Falah, Baniyas, and Al-Shamkha also reported improved average PRD values. For example, Al-Shamkha average PRD value improved from 1.49 to 1.33; this is attributed to parts of the street network being replaced with alleyways which provide efficient shorter connections to parks entrances. The median redundant routs count for samples in this typology is ranging between 24 and 27, suggesting that alleyways have significantly improved route choice, hence connectivity between residential plots and the local parks. The next typology with improved network connectivity, upon the inclusion of alleyways, is the interlocked street pattern with a core. The average PRD values of samples belonging to this typology are all below the 1.5 test threshold (between 1.37 and 1.41). For example, PRD values for Khalifa-city sample improved from 2.00 to 1.40. The inclusion of alleyways has reduced the average block size from 7 to 1 ha or lower, increased the network density from 0.14 to 0.36 km/ha, and the 4-way intersection percentage from 0.04% to 42.97%. All of this group's samples reported a median of RC values between 18 and 26, and RI values are between 3.00 and 3.32 except for MBZ-city sample which has an average RI value of 4.77. MBZ-city's high redundancy index is attributed to its low 4-way intersection density in comparison with other samples from this typology, thus redundant routes are likely to have greater deviations from the shortest route. The East-AD sample with its hybrid typology also showed an improved average PRD value; this is because alleyways mitigated the impact of the compromised route continuity caused by the arterials/ collectors, included, within the park's service area. The median count of redundant routes in this sample is the highest at 119, yet the cumulative length of the alternative routes is on average 3.51 folds longer than the shortest distance suggesting that most of those alternative routes have reasonable deviations from the shortest routes. This is attributed to the significant increase in intersection and network densities (from 2.63 to 5.18 intersection/ha).

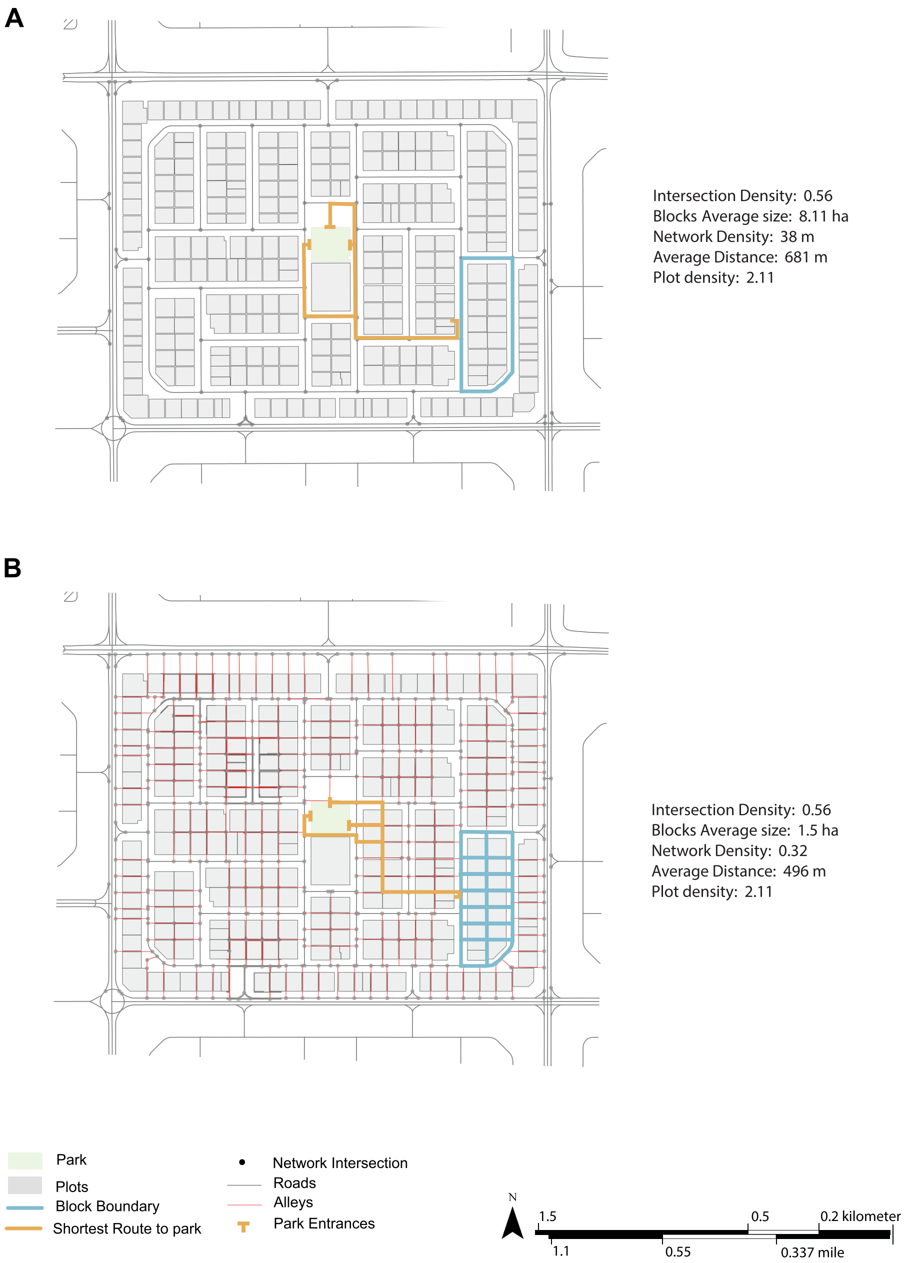

FIGURE 7
MBZ-city sample showing the conversion of the network layout into a gridded one. **(A)** Network scenario streets only. **(B)** Network scenario streets and alleyways.

The inclusion of alleyways in the semi-grid with a core typology samples have resulted in an improved average PRD values for all the samples except Al-Bahya-2. Al-Shahama, Al-Samha, and Baniays-2 samples reported average PRD values of 1.37 or lower, while the average PRD of Al-Bahya-2 has slightly improved from 1.76 to 1.62, a value that is still above the 1.5 test threshold. In Al-Bahya-2, route directness for some plots is impacted by the network hierarchical configuration, where the inclusion of arterials/collectors extends the travel distance and impedes route continuity. This is unlike Baniyas-2 sample, where peripheral plots are connected with alleyways that have direct interface points with arterials/collectors, thus providing more direct continuous routes (see Figure 8). Alleyways in Baniyas-3 sample, with its diagonal parallels typology, resulted in minimum improvement. The reported average PRD value of this sample is still above 1.5 (PRD = 1.58). This is attributed to the compromised route continuity resulting from the diagonal pattern of the block and network configuration. The diagonal network and block configuration increase travel distances relevant to the Euclidean distance. The inclusion of alleyway, however, has significantly enhanced route choice (from a median of 2–29), and the average RI value (at 3.60) suggest that most of

FIGURE 8
Baniyas-2 sample with uninterrupted route continuity against Al-Bahya-2 sample with route continuity impeded by the network hierarchy. **(A)** Baniyas-2 sample with alleyways forming continuous uninterrupted routes to the park. **(B)** Al-Bahya-2 sample with alleyways continuity interrupted by the network hierarchy.

these routes have reasonable distance deviations from the shortest routes.

5 Discussion

Considering the COVID-19 ramifications on daily life activities, connectivity to parks has been forwarded in literature and planning policies as a key quality in post-pandemic neighborhood design. This research assesses Abu-Dhabi neighborhoods as case studies to investigate the impact of network connectivity on walkability to parks within a catchment area of a 1-km network distance, from the parks' centroids. Connectivity is used to assess the network efficiency in terms of route directness and route choice. Route directness is evaluated using Pedestrian Route Directness (PRD), and the route choice is evaluated using two measures: Redundancy Count (RC), which returns the count of alternative routes that are longer than the shortest path by 20% at most, and Redundancy Index (RI), which provides insights on the distance deviations of alternative routes from the shortest route. Findings reveal that, within the catchment area, certain street network typologies and attributes provide more direct routes to parks in comparison with others. For example, samples with the grid-iron and semi-grid layouts are found to have the most efficient networks in terms of route directness, having the lowest average PRD values, when only street networks are considered. On the other hand, and considering only streets networks as well, samples with typologies of semi-grid with a core and interlocked with a core reported higher averages of PRD values. However, those typologies showed more route redundancy, higher median values of redundant routes count, than the samples associated with efficient route directness typologies.

When alleyways are included in the network, route directness and redundancy were observed to increase in all typologies. However, the reported improvement in both the average PRD values and the count of redundant routes in efficient typologies such as grid-iron, semi-grid, and semi-grid with a spine, was less than the reported improvement in the inefficient typologies, which include the semi-grid with a core, interlocked pattern with a core, and hybrids of fragmented and diagonal typologies. This can be explained by the fact that alleyways in typologies that are conducive to walking are less likely to form additional shorter connections, unlike inefficient typologies in which the impact of alleyways is more pronounced. The contribution of alleys with regard to network efficiency is attributed to the transformation of some networks to gridded layouts. Baniyas street's network layout sample, for example, has been transformed from a semi-grid with a service spine into a gridded one, evident from the increase in intersection density (from 0.55 to 2.44 intersection/ha), percentages of 4-way intersections (from 0.04% to 67.72%), resulting in an improved average PRD value (from 1.42 to 1.30). An example of improved values in an efficient typology is the semi-grid with a spine typology, where prior to the inclusion of alleyways, the average PRD values were between 1.42 and 1.49, and the median RC count was at 1. After the inclusion of alleyways, the average PRD values improved to become between 1.30 and 1.33, and the reported median RC counts are between 24 and 27. For inefficient typologies, samples belonging to the interlocked with a core have all reported average PRD values well above 1.5 except one, and median RC values were between 1 and 5. After the inclusion of alleyways, all the samples reported average PRD values between 1.37 and 1.41, and median values are between 18 and 26.

Key findings suggest that gridded and semi-gridded typologies tend to have more direct routes than fragmented or diagonal typologies. Higher intersection densities also increase routes redundancy/choice but are likely to extend travel distances. Typologies with more direct routes to parks provide residential plots with routes that can be traversed at short distances relevant to their location. Their low redundant routes count is attributed to the lower network and intersection densities associated with samples found in such typologies. Residential plots in typologies with less direct networks have higher network and intersection densities and are connected with parks *via* multiple routes. This suggests that, although increased intersections offer the opportunity of multiple routes, that connect the origin with the destination, they are likely to increase the route complexity and therefore the traveled distance. This was observed in multiple studies (Golledge, 1995; Sevtsuk et al., 2021) that associated increase in both the perceived and the actual traveled distance with increased route complexity/turns. It should be noted that this association between route directness and redundancy depends on the typology itself. For example, Al-Shawamekh sample with its semi-grid typology shows both high route directness and redundancy count. Although it has similar network and intersection densities to those samples of efficient networks, its semi-grid typology mitigates the low intersections and the long block faces. Conversely, Baniyas-3 sample, shows both low route directness and redundancy due its diagonal network configuration, despite its relatively high intersection density.

These results show that routes to parks are likely to be impacted by different network's attributes, including: densities of the network itself and its intersections, the average distance between intersections, and the type of streets included in the network. Most notably, typologies seem to exert stronger impact even when sufficient intersections and routes are present within the network. Ensuring appropriate connectivity levels, in terms of both route directness and availability of redundant routes, depends largely on successful implementation of alleyways to overcome route continuity deficiencies resulting from inefficient typologies or network configurations. Current planning policies in Abu-Dhabi would need to consider post-pandemic emergent living preferences with regard to how neighborhood parks can be accessed. The Abu-Dhabi public realm design manual, 2021, prioritizes increasing parks availability in line with the city's 2030 vision. The manual specifies that at the neighborhood level, a minimum area of 2-ha should be designated as a park with a catchment radius of 700-m. Although the manual provides detailed planning and design policies that addresses the park itself and the necessity of having direct connection with pedestrian/cycling routes, it does not take into consideration different neighborhood typologies with regard to network design, hierarchical configuration, as well as alleys distribution and contribution to the network. In particular, the manual is very descriptive in nature, providing design ideals without delving into the design and attributes of the network system. For example, the manual does not consider street typologies in terms of average travel distance, frequency of intersections or routes' diversity. Additionally, throughout the manual, parks entry guidelines mandate the necessity of ensuring direct connection with uninterrupted pedestrian/cycling routes. However, the guidelines do not take into consideration whether residential plots, within the park's catchment area, can access alleyways/pedestrian routes. Therefore, a more comprehensive approach to designing and planning for greater connectivity to neighborhood parks should consider average travel time and the availability of route options to pedestrians, as well as more pedestrian cross points along arterial/collectors. Other guidelines should evaluate the qualitative aspects of pedestrian routes in terms of infrastructure adequacy, suitability of accommodating longer connected walks, and availability of shading and landscape along the path.

6 Conclusion

Regarded as key destinations during the pandemic, neighborhoods' parks had an impactful positive role on the physical and mental wellbeing of residents during the extended lockdown duration. Access to parks was forwarded, therefore, by many policymakers and scholars as a necessity for post-pandemic neighborhood planning and design. This renewed the debate over how different physical features of the built environment support active mobility to parks and open public spaces. Network systems (streets + alleys) are central to this debate where active travel takes place. On this vein, this article evaluated connectivity efficiency of the network systems of Abu-Dhabi neighborhoods. Connectivity, a concept frequently used in urban practice and literature, addresses street networks in terms of the sufficiency of multiple connections between an origin and destinations, and the efficiency of such connection with regard to the traveled distance. Using three measures of network connectivity, 16 samples grouped into 6 different typologies were evaluated. The three measures are: The Pedestrian Route Directness PRD, which assesses whether routes to a park can be traveled at short distances; the route Redundancy Count, which evaluates whether the typology support travel through multiple routes with minimum distance devotion from the absolute shortest route; and the Redundancy Index, which evaluates the efficiency of the alternative routes. Typologies of gridded, semi-gridded, and semi-gridded with a spine networks were found to provide more direct routes, but lower redundant connections to parks unless supplemented with alleyways/pedestrian routes. Conversely, typologies of service core with a semi-grid or an interlocked network, and hybrid typologies of fragmented and diagonal networks were found to support access to parks *via* multiple but less direct routes; therefore, alleyways implementation in such typologies should address network's deficiencies. Overall, typologies with gridded, semi-gridded layouts with consistent street patterns, the ensures route continuity, reported significantly higher connectivity values than typologies with less consistent, fragmented layouts. An example of this is the East-AD sample which, despite having the highest intersection density before and after the inclusion of alleyways, its average PRD values remain among the highest, indicating lower network efficiency.

The study also recommended that current planning and design guidelines, in Abu-Dhabi, should adopt evidence-based and applied methods in drafting planning policies, assessing existing conditions, and revitalizing existing issues in the urban fabric, rather than providing descriptive narratives and idealistic text. The lack of pedestrian data availability is a limitation in this study; future studies, therefore, should consider such data along with other micro-scale route's attributes such as the quality of sidewalks, availability of greenery/shading and mixed land-uses along the routes.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Industrial neighborhoods in desert cities: Designing urban landscapes to reduce sandstorm effects in Mussafah

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Labor housing projects in many Gulf countries are located in less favorable sites in the desert hinterland. They are characterized by grid-based compositions, simple facades, and block buildings positioned on the outskirts of cities. This development type was implemented in the industrial sector of Abu Dhabi, known as Mussafah. Gradually, this industrial area redeveloped its urban fabric by transforming many of its buildings into mixed-use structures with small gardens that provide open air spaces to the community and promote social interaction. Interventions from the community *via* introducing small garden stock increased the sense of belonging, improved the urban fabric, and reduced sand movement in the area. This is important in the Gulf region's desert environment, which gives rise to sandstorms. This study evaluates the amount and distribution of sand around a selected group of buildings in the Mussafah area through experimental work. The methodology involves a coupled air and sand experiment in an environmental wind tunnel. The experiments have shown that adding a fence around the small gardens of the buildings in Mussafah reduced the sand pollution effects significantly.

KEYWORDS

Abu Dhabi, sandstorms, sand movement, Mussafah, industrial neighborhoods

1 Introduction

Pre-petroleum urban enclaves in the Gulf region are scarce. The lack of a coherent fabric of built heritage in Abu Dhabi from the pre-petroleum era made it difficult to use local precedents to create the modern city (Menoret, 2014). Modern Abu Dhabi, which dates to the late 1960s, was planned to reflect many of the principles of "Modernism," which gave emphasis on functionality and a minimalistic approach to the use of materials (Anderson, 1977). This was manifested through the grid street pattern and the construction of superblocks and pragmatic concrete towers as the building stock of the downtown area (Damluji, 2006). Le Corbusier's principles in *La Ville Radieuse* influenced the planning of Abu Dhabi. These principles not only aimed to increase the urban capacity of the modern city but also advocated an improved urban environment and the efficiency of the "Modern" city (Le Corbusier, 1967). These design principles became models for architects planning Abu Dhabi, such as Katsuhiko Takahashi, one of the leaders in the creation of Abu Dhabi's Master Plan in the 1960s, and a strong advocate of Le Corbusier (Montavon el al, 2006). The 1962 masterplan of Abu Dhabi located the industrial areas along with the power station, port, and desalination plant along the entrance to the East Creek. Later plans of Abu Dhabi from

1966 onward placed the industrial zones further east with a gridiron network of roads/zoning beginning to separate the different parts and activities of the city. The 1968 masterplan by Abdelrahamn Makhlouf onward shows that a shift in the main industrial area has materialized toward the desert hinterland, where it is currently located (Bani Hashim, 2018). Despite Abu Dhabi's pragmatic gridiron plan, wide streets and block buildings in the main archipelago included several large gardens, such as Capital Park, Family Park, Dolphin Park, Geneve Garden, Al Mushrif Garden, Umm Al Emarat Park, and Khalidiyah Park. However, no such gardens were planned for Mussafah. Open spaces where workers gather for sporting activities are "informal" open areas, often used as cricket fields by the Indo-Pakistani community.

Ignoring labor housing's much-needed urban infrastructure can lead to decline, as exemplified by the Pruitt–Igoe project, where economic/engineering decisions dictated a Modernist unified block design, eventually leading to decline and demolition (Modern Architecture's Death in St Louis Missouri in 1972) (Bristol, 1991; Jencks, 1991; Mechlenborg, 2019; Perez et al., 2022). In the last decade, new policies and guidelines have been developed, aiming to improve the design and living conditions of workers. The upgrading of local amenities was part of the revitalization of public spaces to foster a sense of belonging to the community (Sahraiyan and Tümer, 2017). Abu Dhabi's recent policies and investment in green areas and cultural institutions/spaces of gathering further changed the perception of residents living in a transit city to residents with a sense of belonging. Urban landscapes in Abu Dhabi are evolving in the form of jogging tracks and cycling paths along the Corniche and the Eastern Mangroves waterfront in addition to new parks such as the Al-Reem Park and the Al-Jubail Mangrove Park.

These new urban landscapes are part of the Abu Dhabi (2030) plan to promote healthier living and better adaptation to the environment manifested *via* green corridors and sustainable growth (Plan Abu Dhabi, 2030). In recent years, a strong drive has been raised for environmentally responsive landscape use of native plants (Hung and Peng, 2017). Municipal authorities are focusing more on water conservation landscapes in all government-funded projects. Abu Dhabi's "Estidama" Pearl Rating system (PRS) further accentuates the ecological values of planting native or adaptive species by offering credit points for planting diversified types of species, including native and adaptive saline-tolerant species (Yagoub, 2014; Alam et al., 2017). The objective of this study is to highlight the importance of community gardens in low-cost housing in industrial neighborhoods as a tool to improve social cohesion and as a means of controlling sand movement in a desert environment, which has repercussions for urban integrity and public health.

2 Mussafah—Abu Dhabi's industrial area

The Mussafah industrial area in the desert hinterland of Abu Dhabi, United Arab Emirates (UAE), represents an example where workers' compounds have been built with functionality and pragmatism governing their design. This industrial city is essential to house the workers that support the large construction industry, which contributes about 9.4% (or about 23 billion USD) of the Emirate of Abu Dhabi's GDP (Statista, 2021). The Mussafah area includes industrial zones with factories and workshops, as well as large workers' camps where service laborers reside. The area is organized by zoning based on the type of industrial activity. Thus, placement of factories, small industries, car agencies, and maintenance workshops is organized according to zoning principles. The overall plan is dominated by a grid street pattern and a freeway that provides quick access to other regions and separates the industrial area from other, mostly residential-dominated areas. This grid street pattern is not only found in the Mussafah area but is also the dominant pattern of the city of Abu Dhabi as a whole. Mussafah's industrial neighborhoods house many of the city's blue-collar workers, taxi drivers, security guards, and other service sector employees. The large labor force in Abu Dhabi is segregated by activity in the form of construction workers living in Mussafah Sanaiya and service sector workers housed in Mussafah Shabiya (Connell and Burgess, 2011). The most prominent labor city in Mussafah Sanaiya is Industrial City Abu Dhabi or ICAD. Here, housing projects are in the form of large rectangular structures within a walled enclosure with recently introduced facilities, such as the ICAD mall (Figure 1A). The scale of the ICAD is massive and bears the same attributes of the low-cost/industrial housing projects.

The recent improvements in Mussafah Shabiya can be attributed to Abu Dhabi's Executive Council, which began to develop a master plan for Mussafah in 2016 known as the Future Vision of Mussafah. This is part of a decade-long transformation of the broader area that included both labor housing projects and the whole industrial area (Dennehy, 2017). Mussafah's developments included a new public garden, installation of light posts and security cameras, street names, enhancement of the transport network, and recreational spaces (Lovell et al., 2014). Older-generation buildings (ground floor + mezzanine +three floors) are being gradually replaced with better-built, taller building blocks (G + M+7; 27–30 m high), many of which include coffee shops, restaurants, and small fenced gardens in front. The conversion of ground floors of buildings into coffee shops surrounded by gardens and small fences (Figure 1B) occurred as a result of improving economic conditions in the broader area and the development of residential neighborhoods of Mussafah (Pasha et al., 2021). Developments by local municipalities led to upgrading the infrastructure in Mussafah, which encouraged the community to upgrade the existing building stock, which, in turn, led to better living conditions and an improved sense of collective ownership (Ng et al., 2011; El Amrousi et al., 2019).

Emerging urban landscapes with jogging tracks, trees, and cycling paths in Mussafah (Figure 1C) have created an urban ecological environment that supports residents' health and well-being through venues for physical activity (Xiao et al., 2020; Afrin et al., 2021; Tan et al., 2021). They also assist in temperature amelioration, especially from the high 40°C temperatures experienced in summer, and provide the benefits of a healthier lifestyle and a sense of identity for the community (Anderson, 1977; Lin et al., 2018; Boros and Mahmoud, 2020; Olivetti, 2022). Introducing such landscape elements in industrial neighborhoods enhances public health and quality of life for its residents (Chiesura, 2004; Mekala et al., 2015). Furthermore, these elements improve outdoor and indoor air quality and reduce noise pollution (Hung and Peng, 2017). Among the challenges of the urban landscape is deciding on the optimal allotment and management of different land use alternatives and

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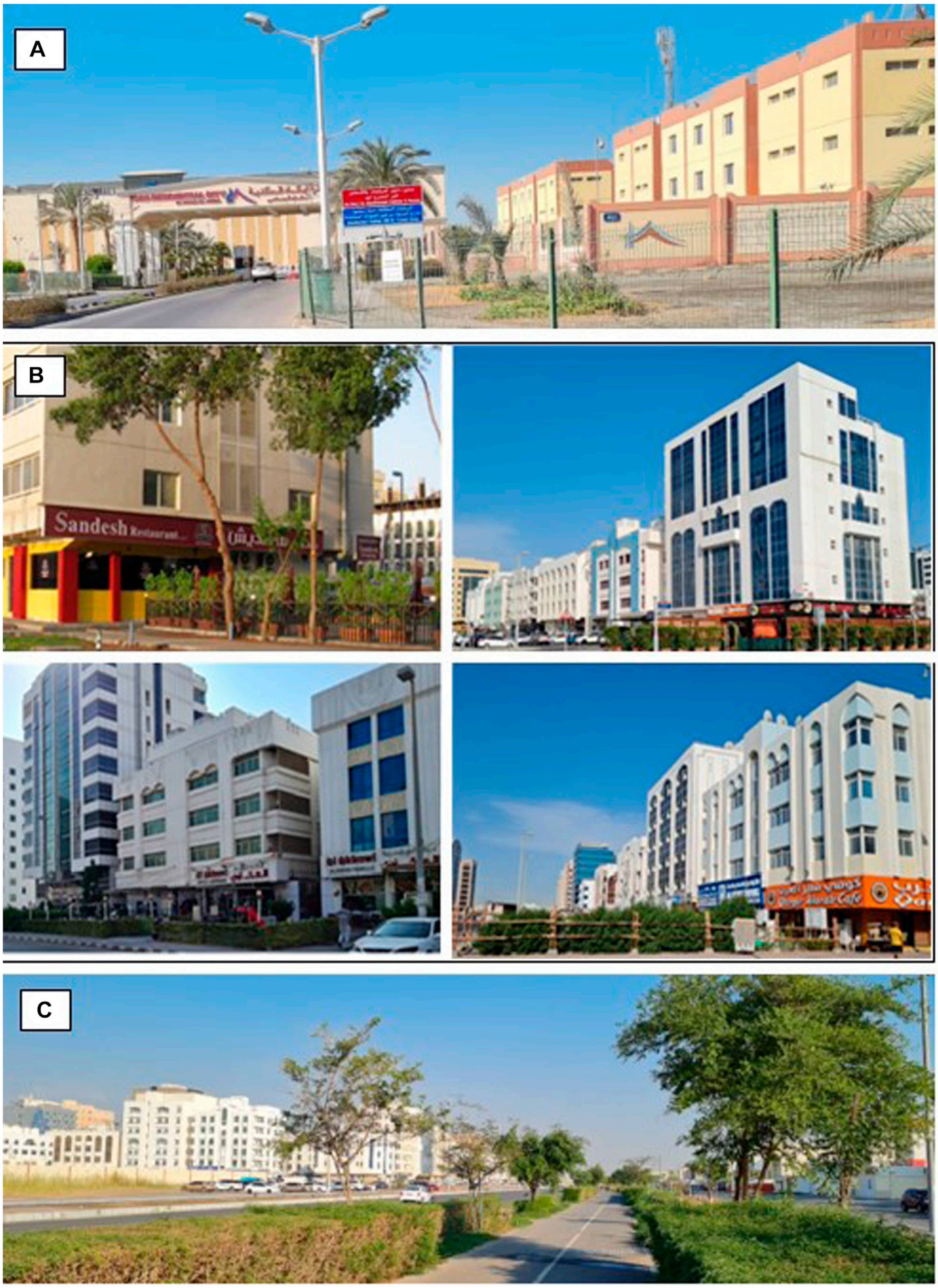

FIGURE 1
Musaffah: **(A)** the Industrial City of Abu Dhabi (ICAD); **(B)** different generations of buildings displaying alternative façade treatments and localized gardens; **(C)** green walkways and jogging and cycling paths leading to bus stops and public transit hubs (photographs by authors).

types of greenery (Keshtkaran, 2019). Exploring how urban landscape solutions can serve important social functions of communities is key to retaining sustainable urban areas and urban parks (Fernández Águeda, 2009; Lu et al., 2017). Creating new urban landscape patterns not only enhances the identity of urban space but also has the potential to reduce

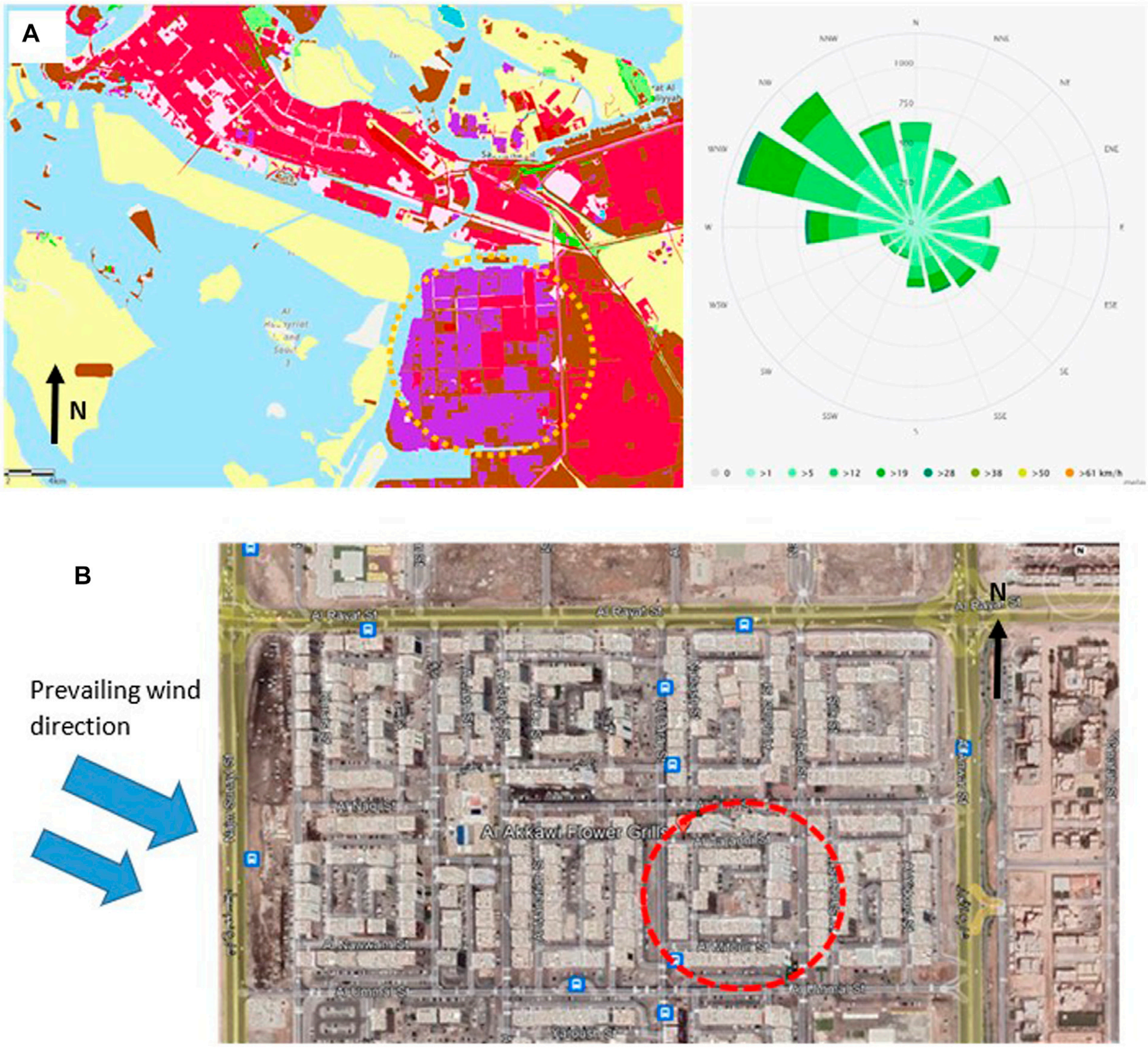

FIGURE 2
Study site and prevailing wind: **(A)** purple indicates the industrial areas in Mussafah; red indicates the mixed-use commercial–residential areas. It can be seen from the wind rose that the maximum wind speed is about 30 km/h approaching Mussafah from the WNW (Source: addata.gov.ae); **(B)** grid street pattern and superblock urban fabric in the Mussafah Shabiya area and prevailing wind direction (GoogleEarth).

pollutants through filtration while also regulating microclimatic conditions (Wheeler, 2004; Taylor, 2007; Hall, 2008).

3 Sandstorms in urban areas

Sand and dust storms are natural phenomena that occur on a large scale worldwide. They are active in drylands, which constitute about half of the world's land area (Awadh, 2023). Sandstorms occur when unchecked, strong, or turbulent winds combine with exposed, dry, loose-soil surfaces. Sandstorms, which are common in semi-arid and arid regions, cause serious environmental problems as a result of strong dry wind blowing over the desert that raises and carries clouds of sand or dust (UNEP, WMO, UNCCD, 2016). It is important to minimize the impacts of sandstorms with early warning systems and regional cooperation. Sandstorms can be tracked using a combination of satellite imagery, ground monitoring observations, and numerical modeling. Dust emission increases over the Arabian Peninsula throughout the spring months as the surface dries, and the near-surface wind speed strengthens. In the United Arab Emirates, the sand dunes of the Rub' al Khali sandy desert, notably in the Sabkha Matti, which extends from the Emirates into Saudi Arabia, provide a source of sand that sandblasts the surface to generate dust storms. In the UAE and Abu Dhabi, the Shamal winds blow from the northwest, as indicated in the wind rose diagram (Figure 2A) and generate dust and sandstorms throughout the year. The higher dust loadings are in late spring and fall (Francis et al., 2022), with the impact of the Shamal winds being more pronounced in urbanized areas (Ng et al., 2011 Kallos et al., 2014; Kallos and Qahtani, 2020). The impacts of

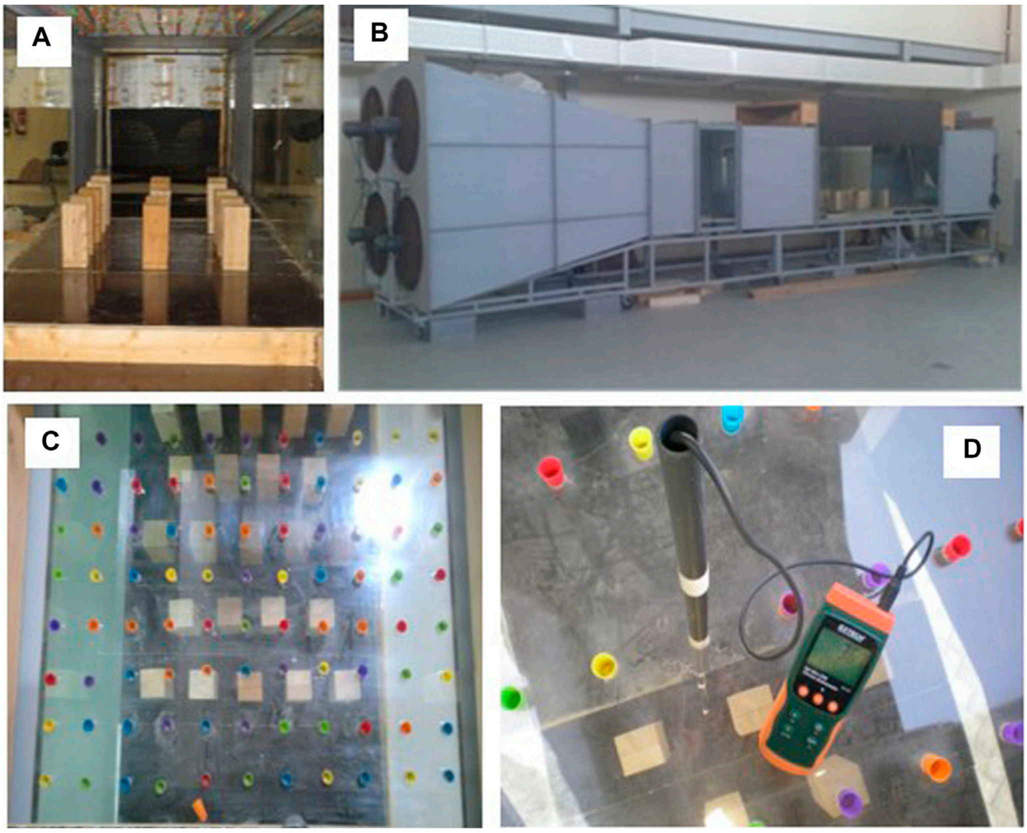

FIGURE 3
Experimental setup: **(A)** block array arrangement; **(B)** environmental wind tunnel; **(C)** holes in the top acrylic sheet and plastic stoppers; **(D)** hotwire anemometer and data logger.

sandstorms are more visible in urban areas where they can cause damage to infrastructure, interrupt transport and communication systems, and cause road traffic accidents. The effect of sandstorms and sand movement is especially visible in areas of affordable housing for lower-income communities, especially in industrial city sections such as Mussafah (Cakmak, 2014).

Urban landscapes enhance the aesthetics of urban spaces in industrial neighborhoods and act as protective measures against sandstorms *via* natural elements, such as trees, shrubs, and vegetation that stabilize the soil. Protection measures include retaining diverse vegetation and minimizing soil or vegetation disturbance in areas where soil types are especially susceptible to wind erosion. When linked to urban landscaping and ameliorative measures, trees as shelterbelts are effective in reducing the impact of dust transportation. Their effectiveness depends on several factors, such as tree type, shape of their crown, spacing, and distancing. Along with trees, hedges bordering jogging tracks (Figure 1C) are effective in protecting the tracks from adverse climatic conditions, in particular sand movement (Abdegalieva and Zaykova, 2016). Windbreaks and shelterbelts deployed at the correct angles and covering sand dunes with mulch can reduce sand deposition in addition to reducing wind erosion in areas behind a fence (Middleton and Kang, 2017). Urban landscapes offer several windbreak options, such as linear arrangements of trees and shrubs around buildings and along roadsides. Furthermore, they offer venues of mitigation/adaptation and potential buffering against sandstorms (Yang and Wang, 2017). On a larger scale, sustaining landscapes are largely influenced by policymakers and urban planners *via* decisions intended to conserve natural resources and

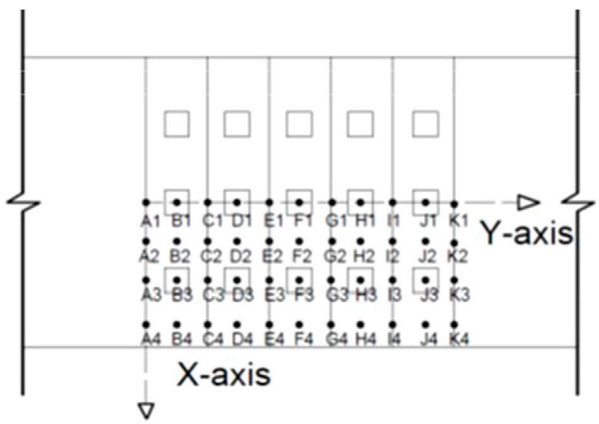

FIGURE 4
Plan view for the locations where the velocity measurements were taken. Note that the spacing in the x direction is 22 cm and the spacing in the y direction is 15 cm.

TABLE 1 Summary of the aerodynamic experimental results.

Point	Coordinates (cm)		Elevation above the bed (cm)						
	x	y	3	8	16	24	27	40	80
A1	0	0	2.73	2.83	2.96	3.88	3.85	3.15	0.98
A2	16	0	3.88	4.55	4.73	4.64	4.67	3.65	1.23
A3	32	0	2.84	3.85	3.61	3.88	4.91	4.67	2.36
A4	48	0	4.54	4.62	4.64	4.97	5.23	4.77	2.47
B1	0	12.5					2.43	3.97	1.15
B2	16	12.5	4.91	5.38	5.54	5.13	4.94	4.18	1.45
B3	32	12.5					3.20	4.80	2.63
B4	48	12.5	5.30	5.40	5.50	5.59	5.27	5.09	2.43
C1	0	25	1.29	1.33	1.25	1.45	2.50	3.82	1.12
C2	16	25	4.57	5.03	5.24	5.19	5.01	4.01	1.95
C3	32	25	1.30	1.30	1.48	1.49	2.33	4.97	2.47
C4	48	25	4.59	4.98	4.63	5.20	5.28	4.95	2.45
D1	0	37.5					3.01	3.88	1.35
D2	16	37.5	3.76	4.52	4.85	4.63	4.84	4.30	2.05
D3	32	37.5					3.41	4.73	3.00
D4	48	37.5	4.44	3.64	4.11	4.96	5.10	5.03	2.83
E1	0	50	1.04	1.22	1.23	1.39	2.38	3.06	1.39
E2	16	50	2.70	3.59	4.32	4.05	4.09	4.17	1.86
E3	32	50	0.98	1.22	1.08	2.42	3.51	4.51	2.61
E4	48	50	3.62	4.54	4.77	4.92	4.99	4.94	2.82
F1	0	62.5					3.29	3.50	1.92
F2	16	62.5	3.10	3.28	3.75	4.10	4.26	4.04	1.78
F3	32	62.5					3.94	4.46	2.91
F4	48	62.5	2.86	3.40	4.05	4.36	4.51	4.88	3.03
G1	0	75	0.94	0.98	1.01	1.84	2.94	3.91	1.82
G2	16	75	2.72	3.47	3.73	3.99	4.33	4.36	2.31
G3	32	75	0.94	1.13	1.07	2.74	3.85	4.57	2.96
G4	48	75	3.08	4.04	5.11	4.77	4.54	5.02	2.71
H1	0	87.5					2.92	3.51	1.85
H2	16	87.5	2.45	3.00	3.60	3.92	3.96	3.92	2.33
H3	32	87.5					3.75	4.52	3.08
H4	48	87.5	2.68	3.69	4.31	4.72	4.81	4.87	2.62
I1	0	100	0.73	1.46	0.79	2.51	3.25	3.56	2.01
I2	16	100	2.54	2.68	3.32	3.56	3.84	3.91	2.43
I3	32	100	0.87	0.94	0.94	3.00	3.93	4.38	2.95
I4	48	100	3.02	3.72	4.58	4.75	4.81	4.55	2.42
J1	0	112.5					2.97	3.38	1.92

(Continued on following page)

TABLE 1 (*Continued*) Summary of the aerodynamic experimental results.

Point	Coordinates (cm)		Elevation above the bed (cm)						
	x	y	3	8	16	24	27	40	80
J2	16	112.5	2.60	2.78	3.47	3.80	3.75	3.56	2.19
J3	32	112.5					4.17	4.42	3.25
J4	48	112.5	2.68	3.48	4.50	4.61	4.88	4.58	3.02
K1	0	125	0.63	0.73	0.80	2.37	3.01	3.47	2.07
K2	16	125	2.45	2.62	3.34	3.53	3.86	4.00	2.32
K3	32	125	0.76	0.79	0.85	2.75	3.64	4.32	3.17
K4	48	125	2.93	3.16	4.25	4.40	4.38	4.31	2.33

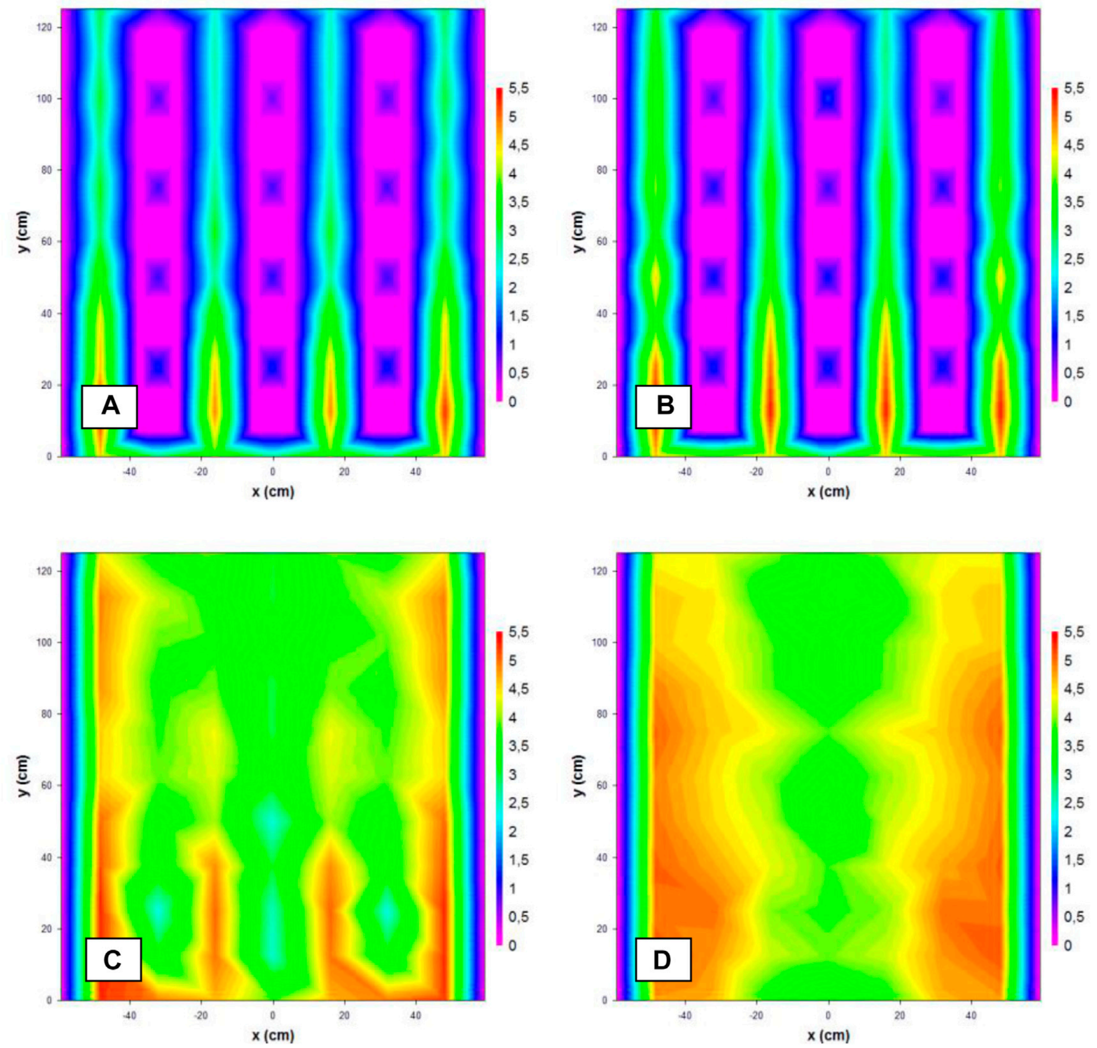

FIGURE 5
Velocity distribution: **(A)** around the buildings 3.0 cm above the bed; **(B)** around the buildings 8.0 cm above the bed; **(C)** above the buildings 27.0 cm above the bed; **(D)** above the buildings 40.0 cm above the bed.

FIGURE 6
Sand patches developed around the simulated buildings in different runs: **(A)** SE1 front-view; **(B)** SE1 sideview.

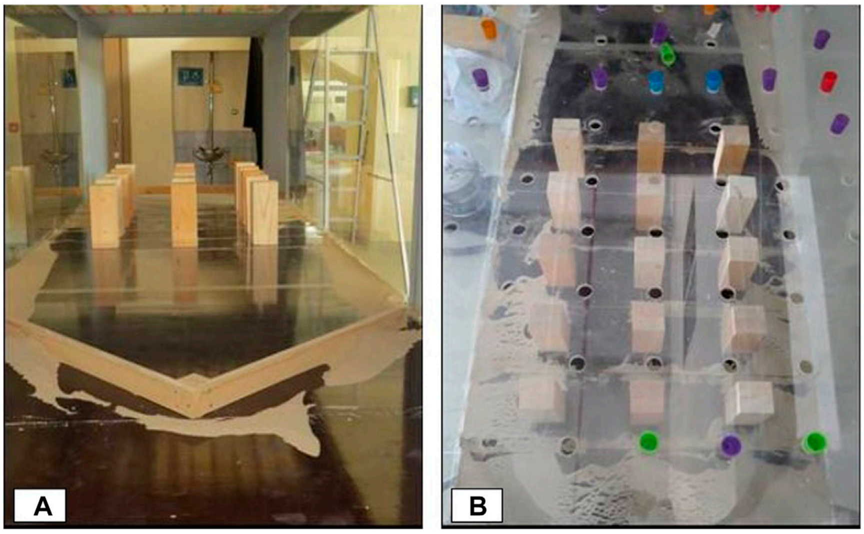

FIGURE 7
Experimental run SE2 with a fence in front of a simulated building: **(A)** experiment arrangement; **(B)** accumulated sand in front of the fence.

water-conserving irrigation technologies (Martin, 2008). Urban landscapes and community gardens are essential to improve public health and protect against sandstorms in industrial areas. Toward the latter goal, our study highlights the effect of fenced gardens in reducing the effect of sand pollution at the pedestrian level through mixed airflow and sand laboratory experiments. This study quantifies the amount of moved sand and the fence effect and highlights the important potential of garden fences to reduce sandstorm pollution effects in desert environments.

4 Methodology

The methodology involves a coupled air and sand experiment in an environmental wind tunnel. Figure 2 shows the study site along with the wind rose at the site. The maximum wind speed is about 30 km/h, and the prevailing wind approaches the study site from the west-north-west. At the pedestrian level, the wind speed can drop to 18–22 km/h. In designing the wind experiment, we simplified the complex random arrangement of the buildings in Mussafah into a uniform array of buildings (Figure 3A). Due to the dimensions of the wind tunnel, we assumed that the prevailing wind approaches the buildings from the west rather than the west-north-west.

The experimental setup includes an environmental wind tunnel and a hotwire anemometer. The experiments were conducted in a wind tunnel designed, built, and calibrated at Abu Dhabi University. The wind tunnel is 8.4 m long and made from galvanized steel and acrylic panels. The cross section of the tunnel at the entrance is 2.4 × 2.4 m and reduces to 1.2 × 1.2 m at the test section *via* a funnel that

TABLE 2 Summary of the sand accumulation experimental results.

Run	SE1	SE2
Sand accumulated in front of the buildings (kg)	2.025	3.870
Sand accumulated around the buildings (kg)	2.375	0.660
Sand accumulated behind the buildings (kg)	0.390	0.180
Sand exited the wind tunnel (kg)	0.210	0.290
Sand in front of the buildings as a percentage of the total amount	40.5%	77.4%
% of sand around the buildings to the total amount	47.5	13.2
% of sand behind the buildings to the total amount	7.8	3.6
% of sand exited the wind tunnel to the total amount	4.2	5.8

TABLE 3 Comparison between the measured sand transport rate and model prediction.

Investigator	q_s (kg/m/hr)
Measured in this study	0.18
Bagnold (1941)	2.56
Kawamura (1951)	0.36
Zingg (1953)	1.29
Owen (1964)	0.32
Hsu (1971)	3.47
Leattau and Leattau (1978)	0.37
Dong et al. (2003)	2.82

has a length of 2.4 m and horizontal:vertical side slopes of 5:1. At the wind tunnel entrance, the bed was made rough, and a honeycomb was placed to ensure straightening of the air streamflow and the full development of the turbulent boundary layer. The test section is made from acrylic panels on both sides and the top for ease of monitoring. It has a length of 2.4 m and is 1.2 m from the wind tunnel exit. The top acrylic sheet of the test section has a total of 253 holes with a diameter of 2 cm, distributed at intervals of 10 cm along the transverse and longitudinal directions of the wind tunnel for data collection (Figure 3). The holes are closed with plastic stoppers that can be removed to insert a hotwire for velocity and airflow measurements. The holes in the top acrylic sheet are accessible *via* a wooden bridge over the test section. The floor of the wind tunnel was lined with 10 wooden platforms serving different purposes. Some of them were for placing and securing the building models or leveling the floor, while others served as sand feeders and sand traps. In the aerodynamic runs (with no sand), the sand feeder and sand trap platforms were flipped. All the wooden platforms sit flush with each other. Wind was generated at the entrance of the tunnel using four mounted industrial pedestal fans manufactured by IGMA. Each has a diameter of 0.76 m, a rating power of 290 W, and a maximum speed of 1,400 rpm. This corresponds to an airflow rate of 5.223 m^3/s and an average velocity of 4.1 m/s. Air velocity was measured with a hotwire anemometer model SDL350 manufactured by EXTECH (Figure 3). The hotwire has a telescoping probe of a length of 1.5 m and diameter of 1.25 cm, which allows taking velocity measurements at various depths inside the wind tunnel. The data logger has a selectable data sampling rate of 1–3,600 s, with a built-in memory card that allows data to be stored and transferred to a computer in the form of an MS Excel file. The data logger reading range is 0.2–25 m/s with an accuracy of ±5 (Elhakeem et al., 2013).

Several experimental runs were conducted in the environmental wind tunnel (Figure 3) using physical models in the form of wooden blocks. The dimensions of the blocks were 10 × 10 × 25 cm. The spacing between the buildings was 15 cm in the longitudinal direction and 22 cm in the transverse direction (Figure 4). Two sets of experiments were conducted in the environmental wind tunnel. The first set involves aerodynamic experimental runs without sand. The aerodynamic experiments were conducted first to describe the airflow pattern around the blocks. They were followed by sand experiments to investigate the formation of sand patches around the blocks. Detailed velocity measurements were collected using a hotwire. Because of the symmetrical arrangement of the buildings along the y-axis (Figure 4), the measurements were taken only at half of the model section. Figure 4 shows a plan view of the locations where the velocity measurements were taken. Seven velocity measurements were taken at different heights at each location around the blocks to predict the velocity distribution at each elevation. Three velocity measurements were taken above the simulated buildings.

For the aerodynamic experimental runs, the proposed physical buildings were placed in the model section. Then, the fans were switched on at the full speed of 1,400 rpm, and detailed velocity measurements were collected in each run using the hotwire. To take the measurements at a desired location, the hotwire was inserted from the top through the holes in the top acrylic sheet. The readings were recorded at different heights, and the hotwire was then moved to the next location. The recorded measurements were stored in the digital anemometer's memory card and later transferred to a computer. The procedure was the same for the sand experimental runs, where the proposed fences were placed in the model section, and a 2-cm layer of the experimental sand was placed in front of the buildings. Enough sand was placed to feed the model section as the runs were expected to last for several hours. Additional sand was added to the sediment feeder during the runs, if needed. The fans were switched on at the full speed of 1,400 rpm and ran until the sand patches around the buildings reached a quasi-equilibrium condition when their shapes no longer changed considerably. The duration of the runs was about 7–9 h to reach the equilibrium condition. Pictures were taken periodically during the run to record the sand patch patterns around the buildings and the fence. After completing each run, the fans were stopped, and the sand around the buildings and in the sediment trap downstream of the buildings was collected *via* a vacuum cleaner and weighed. The wind tunnel was cleaned of sand before the start of the next run.

5 Results

In this section, the aerodynamic experiments are presented by first describing the airflow pattern around the buildings, followed by the sand experiments and the sand patches formed around the buildings. The different runs were conducted with a constant airflow rate of 7.462 m^3/s and a mean air velocity of 5.86 m/s (21 km/h). This air velocity corresponds to the wind speed at the pedestrian level in the study site. Table 1 shows the collected velocity measurements around and above the blocks, while Figure 5 shows contour maps for the velocity distribution around the blocks at heights of 3.0 and 8.0 cm above the bed and above the buildings at heights of 27.0 and 40.0 cm above the bed. The pink squares in Figures 5A, B show the location of the simulated buildings in the wind tunnel testing section. These pink squares disappear in Figures 5C, D because the measurements were taken above the buildings. The figure shows high-velocity values between the building in the transverse direction and very low-velocity values in the airflow direction (Figures 5A, B). The low velocity is common in the wake region behind the buildings. Above the buildings, there is less variability in the velocity magnitude because there is no retarding effect from the buildings. As can be seen from the figures, a complex airflow pattern developed between buildings compared to the pattern formed above the building. One limitation to the aerodynamic results is that the flow in the wind tunnel is unidirectional, while, in reality, it changes with time. Therefore, although Figure 5 provides useful information about the airflow pattern around the building, the experimental airflow may deviate from the airflow on the physical site. Nonetheless, the model experiments have given a- better understanding of the airflow–structure (buildings) interaction.

The sand experiments involve two experimental runs with uniform sand of a mean diameter of 0.17 mm to evaluate the amount of sand that accumulated around the buildings. The first run (SE1) was conducted with arrays of buildings of the same height. The second run (SE2) was conducted with the same arrays of buildings used in run SE1. However, a V-shaped fence with an angle of 90°, side length of 70 cm, and height of 5 cm was placed in front of the buildings in run SE2 (see Figure 7). Like the aerodynamic runs, the sand runs were conducted with a constant airflow rate of 7.462 m^3/s and a mean air velocity of 5.86 m/s (21 km/h). The duration of the runs was about 7.0–9.0 h, when the sand patches around the buildings reached a quasi-equilibrium condition wherein their shapes did not change considerably with time. Figure 6 shows the sand patches developed around the buildings for run SE1. It can be seen from the figure that the sand was concentrated more between the last three rows of buildings. This can be attributed to the wake effect of each building on another. Adding the fence in run SE2 reduced the amounts of sand that accumulated between the buildings tremendously (Figure 7). Although the fence reduced the amount of sand that accumulated between the buildings, Figure 7 shows that much sand accumulated at the sides and in front of the fence. The -fence changed the sand distribution from areal pollution distributed over the entire area where the buildings are located into point pollution (i.e., strip pollution along the fence). The sand pollution can be easily collected from the fence.

Table 2 summarizes the total amounts of sand accumulated in front, around, and behind the buildings for different runs and the amounts of sand in suspension that exited the wind tunnel. The total amount of sand used in each run was 5 kg. The table shows that 47.5% (2.38 kg) and 13.2% (0.66 kg) of total sand used in the experiments accumulated around the building for runs SE1 and SE2, respectively. This proves that the arrangement and spacing of the buildings were optimal and effective in minimizing the sand pollution around the buildings. Adding the fence in run SE2 provided the best results by reducing the amount of accumulated sand around the buildings to 13.2% compared to 47.5% in run SE1. The angled fence used in run SE2 increased the amount of sand that accumulated in front of the fence to 77.4% compared to 40.5% in run SE1. Thus, although the fence improved the environment around the buildings significantly, most probably it will affect the environment upstream of the buildings. The- fence changed the sand distribution from an areal pollution distributed over the entire area into a point pollution (i.e., strip pollution along the fence), which can be easily collected from the fence.

Several sand transport models were developed from airflow over a flat bed; the measured sand transport rate has been compared to these models. Values for shear velocity used in these models were obtained from the approaching velocity (U) over a smooth flat plate as follows:

$$u_* = U\sqrt{f/8}, \tag{1}$$

where f is the friction coefficient of the wooden platforms used in the experiments taking a value of 0.013. The critical shear velocity used in the models was obtained from Zanke (1982). Table 3 summarizes the measured values and the values obtained from different sand transport models. It can be seen that the models provide higher values than those measured in this study. The deviation can be attributed to the effects of the buildings.

6 Conclusion

The impact of sandstorms on the integrity of buildings and the urban fabric of industrial neighborhoods in desert hinterlands is challenging. Throughout this research, we aimed to highlight the role of the urban landscape in improving the environment and reducing the effects of sandstorms in Mussafah. Local gardens and shaded jogging and cycling tracks in Mussafah have improved living conditions and offer a sense of belonging for multi-ethnic communities in an industrial neighborhood. Adding shrubs and green fences in front of the buildings provided the best results by reducing the amount of sand that accumulated around the buildings by almost 34% compared to a run with buildings of the same height and no fence. The fenced garden changed sand accumulation patterns from a non-point distribution over the entire area to strip pollution along the fence that is easier to deal with. Thus, the experiments indicated that it is possible to offer different scenarios for the layout of buildings and protect them through provisions such as small gardens and trees that create barriers and reduce the impact of sandstorms.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbuil.2023.1158543/full#supplementary-material

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The effect of building height on thermal properties and comfort of a housing project in the hot arid climate of the UAE

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A city's microclimate is greatly impacted by urbanization. The ratio of building height to street width affects the thermal properties of urban canyons. This characteristic is one of the main elements that control the thermal radiation emitted and how much solar radiation is absorbed, causing the urban air temperature to be much greater than in rural areas (urban heat island effect). The main aim of this study is to examine the thermal effect of the variations in the height of housing buildings on the urban layout and canyons in the hot arid climate of the UAE. The study used a qualitative method based on ENVI-met software and a case study of an existing housing project to investigate the current situation and the future thermal conditions of proposed configurations. The study investigated two groups of configurations with unified and diverse heights. The results of the study found that the best case among the first group of configurations with unified heights was U3, which had unified mass heights reaching 20 m height, the highest H/W ratio, and the lowest sky view factor; it recorded 0.5°C reduction in the 2:00 p.m. air temperature compared to the base case. The results also revealed that in the case of diverse heights, it is better to locate the highest masses in the hot wind direction. The D2, with highest masses of 20 m height that were located only on the north and west sides of the area blocking the hot north-west prevailing wind, recorded a reduction about 0.9°C compared to the base case. Moreover, in the cases with lower air temperature, U3 and D2 recorded the best predicted mean vote readings, especially in the daytime, when the air temperature is highest.

KEYWORDS

building heights, sustainable housing projects, PMV, hot areas, width-to-height ratio, sky view factor

1 Introduction and literature review

The most significant step for architectural designers is creating livable and environmentally friendly cities by establishing a sustainable urban form (Burton et al., 2013). Sustainable cities provide the users with a healthy mix of housing, commercial, and leisure facilities while meeting the needs of their residents and allowing them to easily access various locally provided facilities and transport nodes along comfortable paths (Moreno et al., 2021). Including passive design solutions in the level of urban design, such as increasing the level of shading, can help improve the thermal conditions in outdoor areas.

1.1 Building heights and urban heat islands (UHIs)

The urban heat island (UHI), which is the rise in temperature in urban environments, has increased in modern cities and communities. The demographic and activity makeup of metropolitan areas, in addition to the neighborhood layouts and designs of contemporary locations, all contribute to this effect (Detommaso et al., 2021). According to Salvati, Roura, and Cecere (2017) and Elmarakby et al. (2022), the UHI in modern districts increases building energy use and hastens climate change. Moreover, physical health, comfort, and development are facing difficulties as a result of the interaction between local UHI and global climate change. Because most people in the twenty-first century live in cities, preventing urban overheating is becoming more and more important (Santamouris et al., 2019). As Bueno et al. (2014) stated, UHI reduces heat evacuation through convection in metropolitan districts, particularly newer ones. In this situation, a variety of alternatives, including passive design solutions, such as increasing the shaded areas due to building height variation, can be incorporated into the planning of contemporary urban neighborhoods. UHI raises the temperature of urban areas, including urban centers, relative to rural and suburban areas, which raises the energy consumption of cities. Sangiorgio et al. (2020) mentioned that building height is the 8th of 11 factors that affect the absolute max UHI phenomenon.

Variations in building height can create a positive effect on the thermal performance of the area. Tall buildings could shade the streets and structures underneath, lowering the quantity of direct sunlight and, thus, the amount of solar radiation absorbed by these structures. It has been shown that spatial arrangement has a significant impact on air temperature. Moreover, the ventilation in a city can be impacted by tall structures. To improve ventilation and lessen the UHI effect, tall buildings can, for instance, produce a chimney effect where hot air is sucked up and away from the street level. Lan and Zhan (2017) stated that increasing the building height and density inevitably results in greater building shades. They added that building height is one of a group of parameters that together account for greater variance in outdoor air temperature. To reduce the UHI effect, they strongly advise that spatial organization be considered in future urban planning. Zheng et al. (2019) confirmed that vegetation and surfaces with tall structures of various heights are the two main types of land cover that have an impact on the thermal environment of the land surface and urban areas. They added that the land surface temperature fell from low-rise to high-rise residential buildings, and temperatures were lowest in high-rise residential areas. Shareef and Abu-Hijleh (2020) confirmed that compared to an urban layout with moderate variation in building heights, one with a large fluctuation in building heights led to a greater drop in outdoor air temperature.

1.2 Effect of building heights and height-to-width (H/W) ratios on the outdoor air temperature

Shishegar (2013) affirmed that in urban design, the variation in building height creates different height-to-width (H/W) ratios and urban layout and affects the outdoor air temperature and the wind speed. Moreover, she added that a street canyon's H/W ratio has a

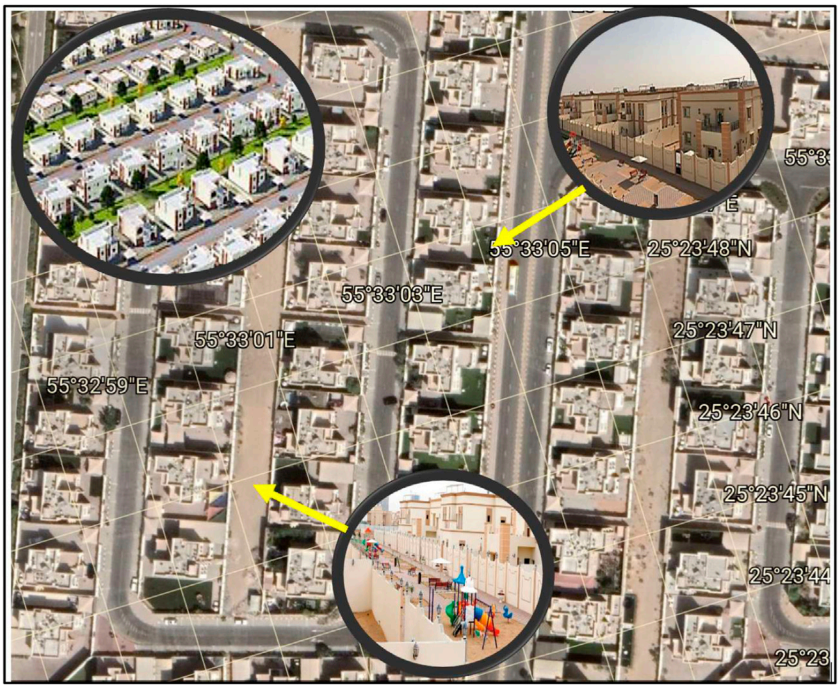


FIGURE 1
Housing project (SZHP), the modern residential urban fabric—Raqaib 2 (Al-Raqaib housing, 2021a), (iskanZayed, 2021), 2 (Al-Raqaib housing map, 2021b).

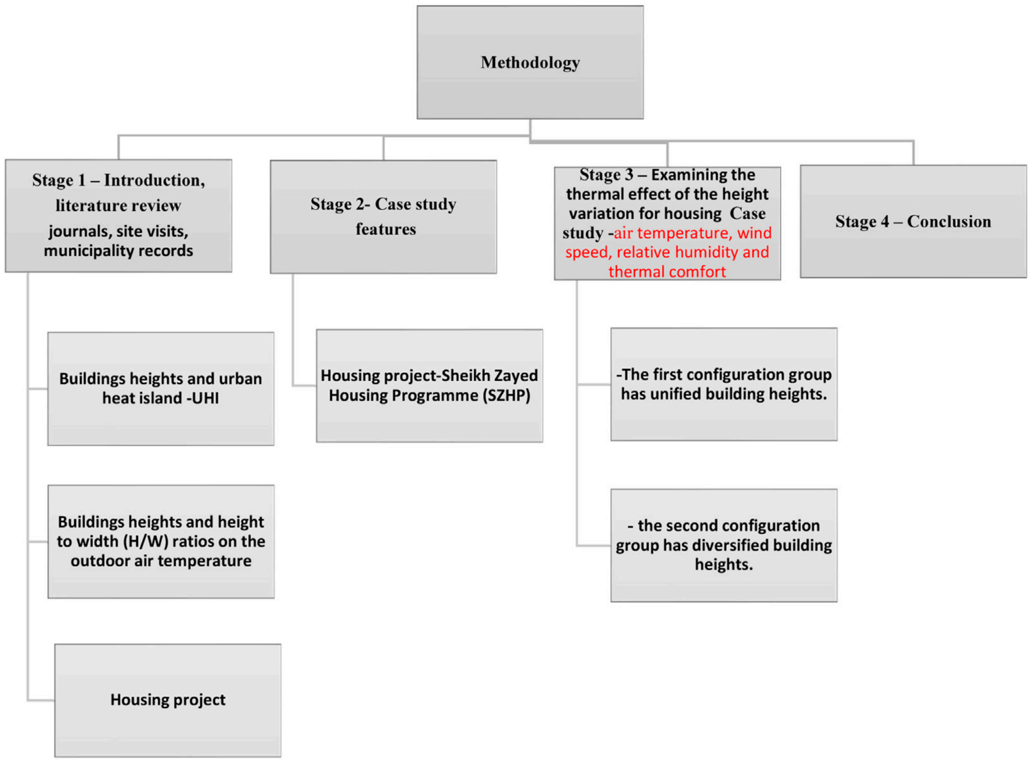


FIGURE 2
Methodology layout.

major impact on how much solar energy is absorbed by buildings and the land between them. The amount of solar energy collected by the roadway surfaces rises as the H/W ratio is reduced. However, the varied surfaces of the urban roadway do not all receive this solar energy evenly. Basically, compared to vertical surfaces, the horizontal earth absorbs extra radiation from the Sun. Thus, the H/W ratio affects the earth's surface temperature more than the facades and vertical surfaces. Placing a tall building next to a low-rise building causes the wind to increase by 90% and reduces the temperature by 1°C; thus, integrating a few high-rise buildings strategically will help increase the wind velocity inside the created canyon and thus decrease the air temperature (Priyadarsini and Wong, 2005). Heat is trapped in long, deep canyons with a high H/W ratio, and the air temperature rises. The airflow is effectively accessed by low H/W ratios of less than 0.3, and a significant amount of outdoor air flows through the canyon to lower the air temperature (Shareef and Abu-Hijleh, 2020).

Gamero-Salinas et al. (2021a) mentioned that considering the building form parameters (such as the height-to-depth ratio, open space ratio, and green plot ratio) that enhance air movement and lower the mean radiant temperature can provide thermally comfortable environments for typical social activities. The most thermally comfortable spaces for all activities during a normally warm hour are vertical and horizontal breezeways (Gamero-Salinas et al., 2021b). Dou (2014) stated that to enhance thermal comfort and lessen the consequences of climate change in urban settings, more compact urban forms with deeper urban canyons and green building coverings are recommended.

Li and Donn (2017) examined the relationships between urban heat islands, vertical temperature lapse rates, and the impact of tall structures on urban wind flows. They claimed that the outside temperature on the top floor of a 30-floor building would be 0.65° lower than on the bottom. They added that wind speeds also rise with height in the atmospheric boundary layer. In addition, tall buildings may experience an increase in heat loss from top stories as a result of simultaneous air pressure and velocity increases. Aflaki et al. (2014) mentioned that the air temperature inside the higher-floor unit is cooler than the lower-floor unit. The large difference in indoor air velocity between the lower and upper levels can explain this. According to Sangiorgia and Santamouris (2020), changes in building height have the most effect on whirlwind features because the height differences cause whirlwinds to grow proportionately, which in turn influences the air temperature and the weather. Salvati et al. (2017) stated that the average building height, which impacts structures' solar gains, and maximum urban air temperatures, has emerged as the most crucial factor in urban morphology in regions with intense solar radiation and a narrow daily air temperature range. In the settings examined in such studies, a strong negative association (R2 = 0.7171) between the average building height and the cooling energy demand was discovered. Boudoukha and Zemmouri (2021) made an assessment based on measurements taken *in situ* throughout the summer and winter at various microclimate conditions. Their study compared two existing city apartment blocks and found that the taller one resulted in lower outside temperatures during the winter and summer. Also, the building's passageway enhanced the accessibility and ventilation

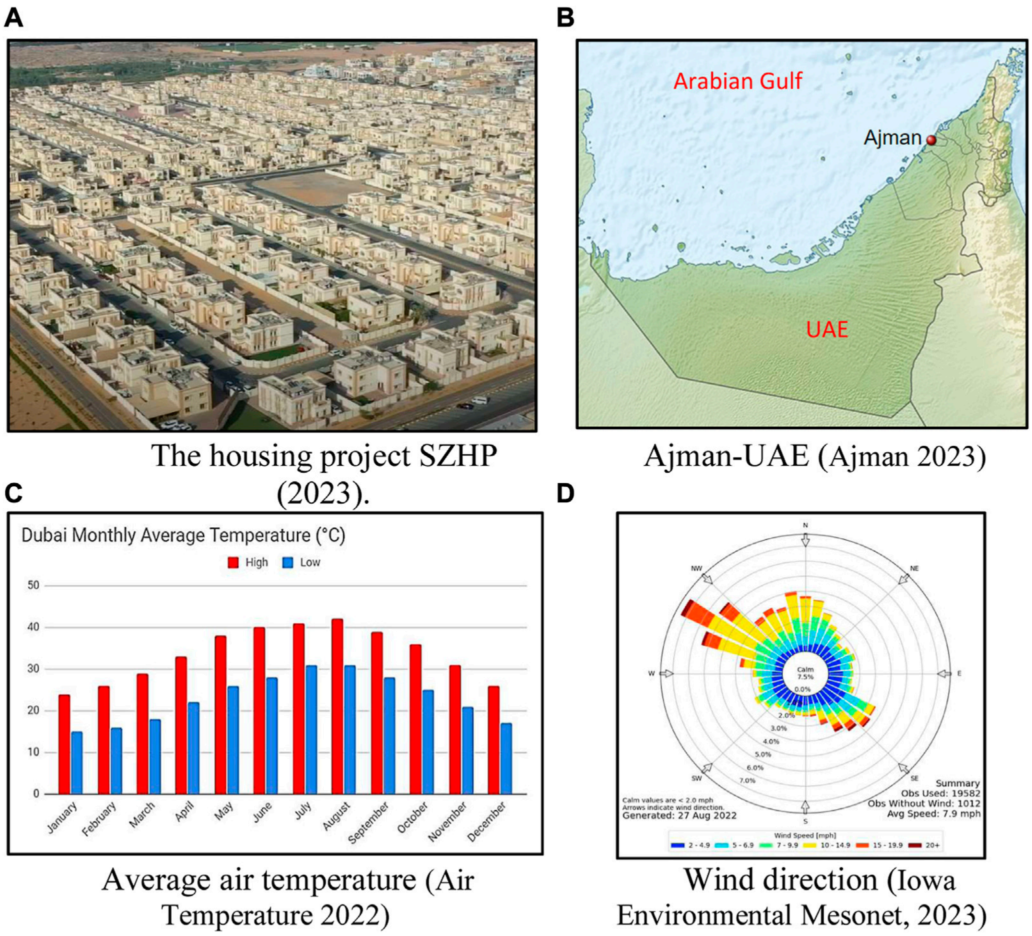


FIGURE 3
Location and climate conditions for the case study, **(A)** The housing project SZHP, **(B)** The location map of Ajman city, UAE, **(C)** Average air temperature- Dubai, **(D)** The wind direction and speed in UAE.

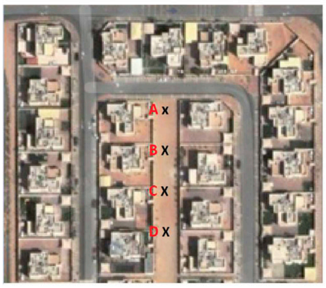
in a city block's inside corner, but it may also increase wind speed, which could be uncomfortable for pedestrians. Zhang et al. (2020) stated that, in winter, a 10 m increase in street width resulted in a 0.17 ˚C increase in daytime temperature, whereas a 10 m increase in building height resulted in a 0.06 ˚C decrease in daytime temperature for the same street width. The number of floors in a building had a substantial impact on the daytime average temperature; however, when a building had more than 20 floors, the temperature did not change much with the height of the structure. Yang and Li (2015) mentioned that as building heights rise, the average urban albedo falls, and more solar radiation is generally absorbed as building height inequalities widen. Thus, a medium-density city with high-rise buildings and significant building height differences has the lowest average urban albedo.

1.3 The case study—Housing project

The case study for this research is a plot area in the Sheikh Zayed Housing Programme (SZHP) (Figure 1) in the Al-Raqaib neighborhood in Ajman, United Arab Emirates, with a contemporary residential urban fabric. The 306 detached, two-story villas in this district are part of a modern neighborhood with modern architectural features, including setbacks and open areas. The layout of the neighborhood is made up of ordered and separated roadways and horizontal and vertical rows of residential buildings. Around 11 open boulevards and outdoor areas of various sizes and shapes are included in the fabric. The purpose of the boulevards is to promote neighborhood gatherings and safe social interaction away from the noise and danger of the primary automotive traffic routes, particularly for children and young adults. The individual units in this area are surrounded by 11 outdoor common spaces. Some of the outside open spaces are as wide as 15 m. The existing housing project's broad roadways and low-height dwelling units reduced the quantity of shade, which increased the outdoor temperature, on one hand, and produced uncomfortable thermal conditions for the users on the other.

As the case study housing project for this research is located in the hot arid climate of the UAE, the outside temperature setpoint (OUT_SET) in the UAE differs according to the annum timing. OUT_SET refers to the desired temperature set by a building or heating or cooling system to maintain the indoor temperature, which is typically influenced by the outdoor temperature. In the UAE, during the hot summer months, the OUT_SET may be set

A

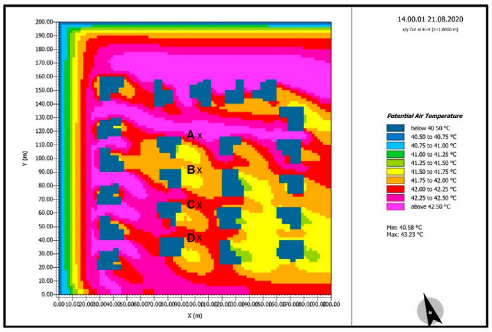


field measurements of four points (Al-Raqaib housing map, 2021).

B

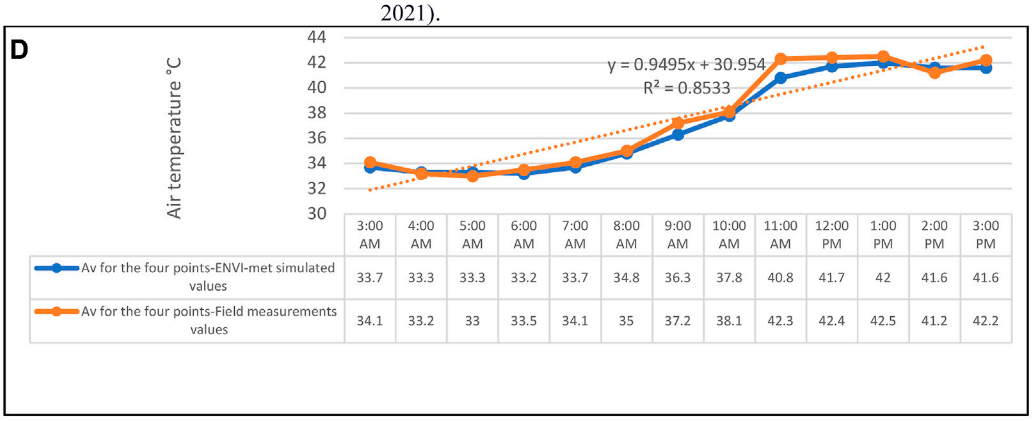
Extech 45170 meter (Extech, 2021).

C



ENVI-met simulation results -Case study plot- 2 pm on August 21.

D



Correlation between measured and simulated temperature data.

E

	Predicted -ENVI-met	Actual-Field measurement	Differences between predicted and actual values	Squared differences between predicted and actual values
3:00 AM	33.7	34.1	-0.4	0.16
4:00 AM	33.3	33.2	0.1	0.01
5:00 AM	33.3	33	0.3	0.09
6:00 AM	33.2	33.5	-0.3	0.09
7:00 AM	33.7	34.1	-0.4	0.16
8:00 AM	34.8	35	-0.2	0.04
9:00 AM	36.3	37.2	-0.9	0.81
10:00 AM	37.8	38.1	-0.3	0.09
11:00 AM	40.8	42.3	-1.5	2.25
12:00 PM	41.7	42.4	-0.7	0.49
1:00 PM	42	42.5	-0.5	0.25
2:00 PM	41.6	41.2	0.4	0.16
3:00 PM	41.6	42.2	-0.6	0.36
The he average of the squared differences between predicted and actual values				0.38
The square root of the the average of the squared differences between predicted and actual values (RMSE)				**0.62**

RMSE for the predicted and actual values

FIGURE 4
Validation information (Salameh, Mushtaha, and El Khazindar, 2022), **(A)** The four points of field measurements, **(B)** The Extech meter, **(C)** The ENVI-met simulation results at 2:00 pm, **(D)** Correlation between the measured the simulated air temperature, **(E)** RMSE for the actual and predicted values.

TABLE 1 Base case: Al Ragaib housing district characteristics (existing configuration).

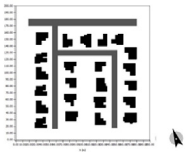
Location map	Ground and built-up area	Plot area	Urban layout	Street orientation	Street width	Building type
		Plot area = 200 × 200 m^2	Grid pattern layout	 NE-SW	Straight and wide, reaching a width of 15 m	Residential, detached houses

TABLE 2 Case study: Al Ragaib housing district characteristics (two proposed configuration groups).

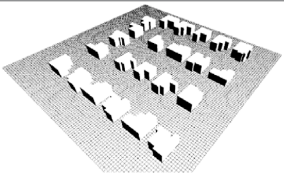
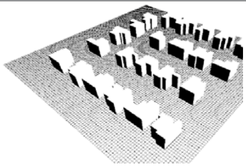
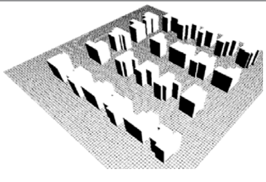
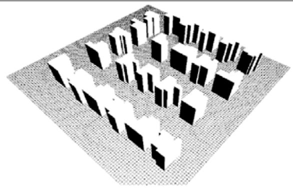
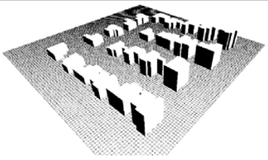
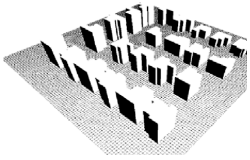
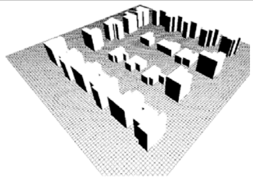
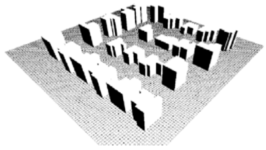
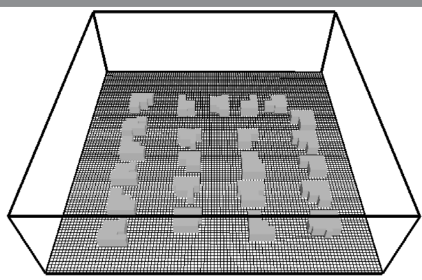
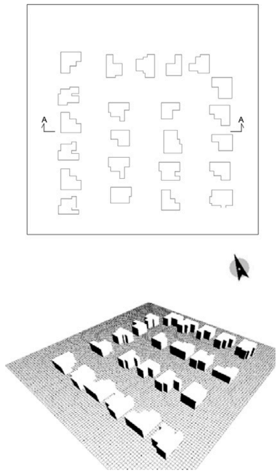
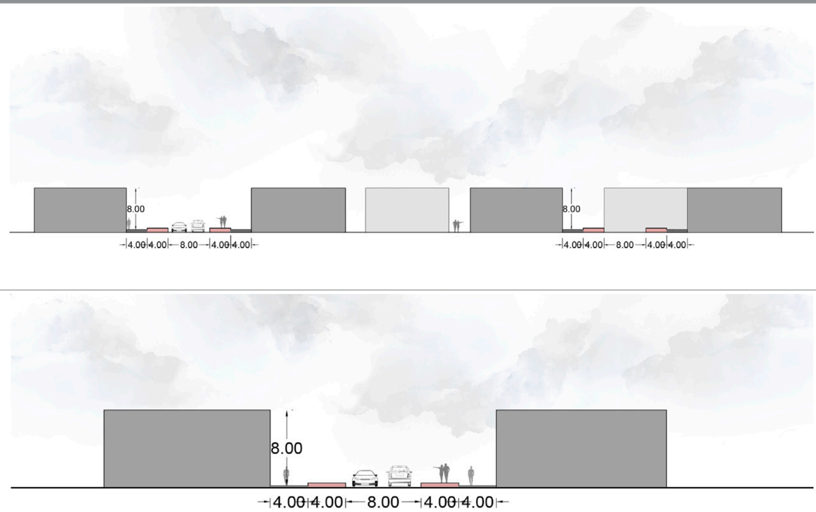
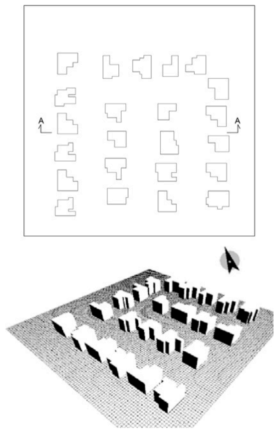
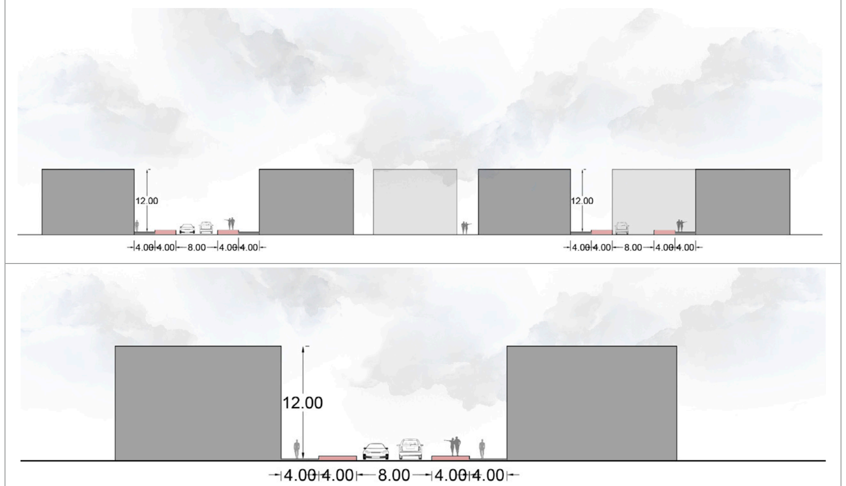
Base case	a- The first configuration group has unified building heights		
			
B1 = 8 m	U1 = 12 m	U2 = 16 m	U3 = 20 m
b- The second configuration group has diverse building heights			
			
D1= 20:16:12:8:8 m	D2 = 20:16:12:8 m	D3 = 20:8 m	D4 = 20:12:8 m
A gradual decrease from the south direction	A gradual decrease from the north-west direction	Courtyard effect	A semi-courtyard effect from the north-west and south directions

TABLE 3 Case study simulation model geometry and conditions (Salameh and Touqan, 2023).

a- Case study model geometry and conditions		b- Working space
Model geometry and conditions	Details	
Cell size	2 m × 2 m × 2 m (*dx, dy, dz*)	
Grid sum	100 × 100 × 25 (*x, y, z*)	
Total time run for each simulation	36 h	
Climate	Ajman, UAE	
Construction materials	Moderate wall insulation and roof insulation	

b-Unified materials thermal properties for all cases				
Thermophysical properties	Thermal conductivity (W/m K)	Density (kg/m3)	Specific heat (kJ/kg K)	Albedo
Concrete pavement light	1.37	2076	0.88	0.25–0.70
Default wall: Moderate insulation	1.4	2350	0.88	0.25–0.70
References	Nikiforova et al. (2013) Oktay et al. (2016)	Nikiforova et al. (2013), Oktay et al. (2016)	Oktay et al. (2016), Kodesová et al. (2013)	Kotak et al. (2023) An et al. (2017)

TABLE 4 The first configuration group has unified building heights.

3D geometry		Urban geometry	Building height (m)	H/W	Built-up area
Base case	 B1 = 8 m		8	H/W = 0.33	10,400 m^2
First group of configurations (unified building heights)	 U1 = 12 m		12	H/W = 0.50	15,600 m^2

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lower to

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TABLE 4 (*Continued*) **The first configuration group has unified building heights.**

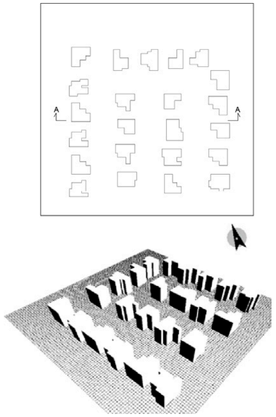
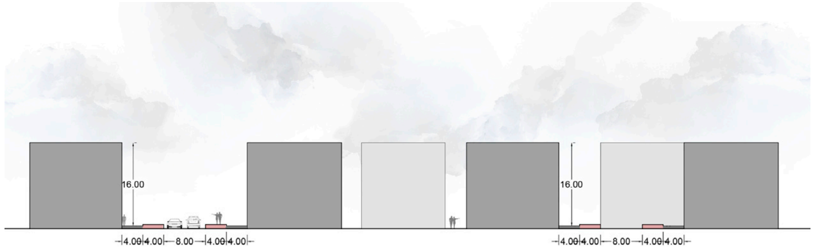
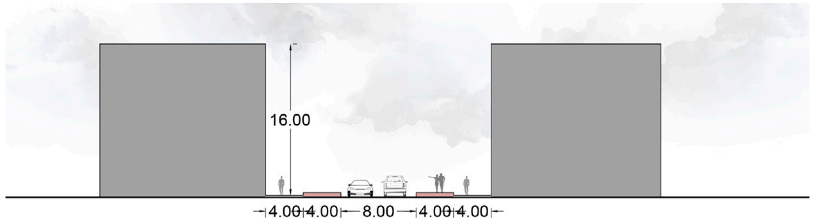
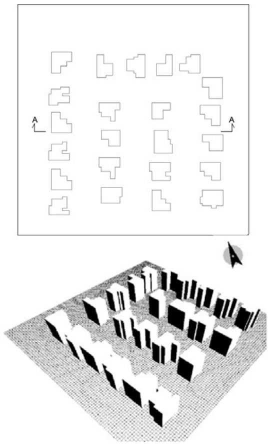
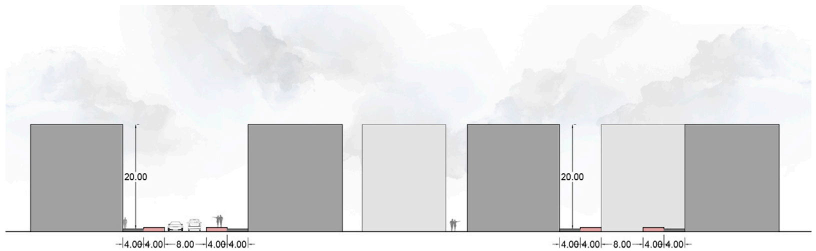
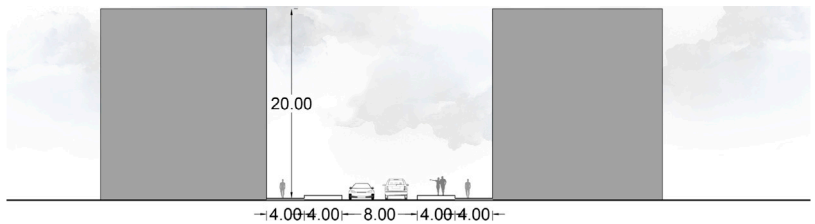
	3D geometry	Urban geometry	Building height (m)	H/W	Built-up area
	 U2 = 16 m	 	16	H/ W = 0.66	20,800 m^2
	 U3 = 20 m	 	20	H/ W = 0.83	26,000 m^2

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TABLE 5 The second configuration group has diverse building heights.

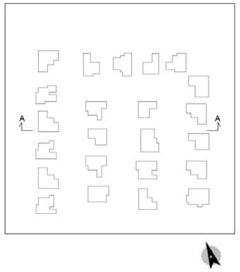
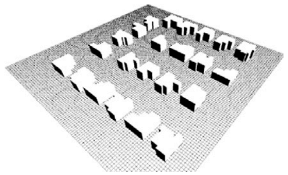
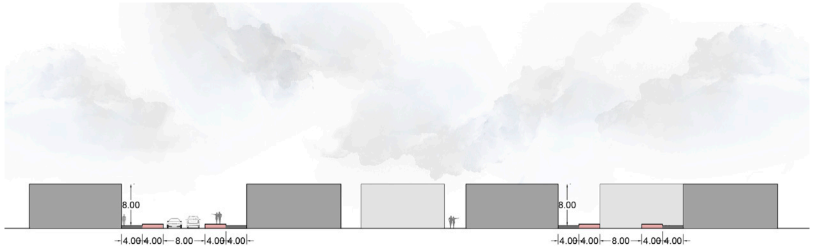
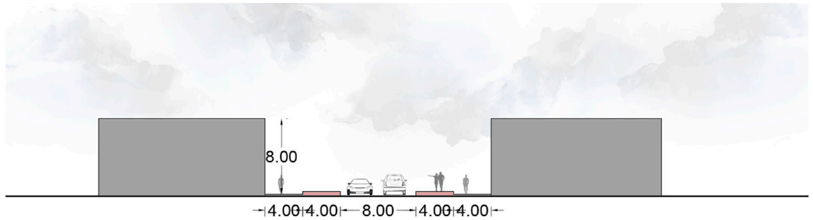
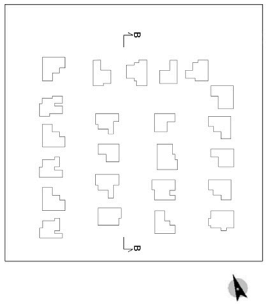
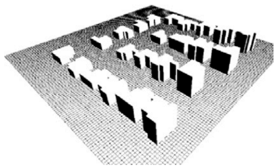
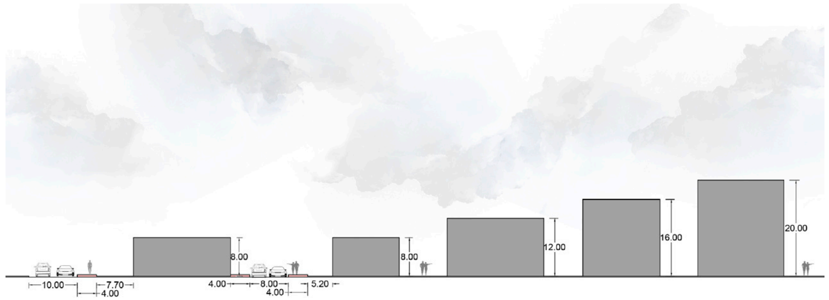
3D geometry		Urban geometry	Building height	Built-up area
Base case	  B1 = 8 m	 	8 m	10,400 m^2
Second group of configurations (Diverse building heights)	  D1 = 20:16:12:8:8 m A gradual decrease from the south direction		20:16:12:8:8 m	15,300 m^2

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TABLE 5 (*Continued*) The second configuration group has diverse building heights.

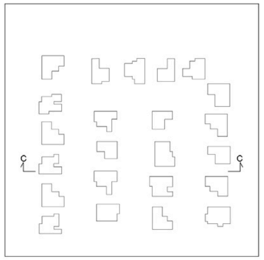
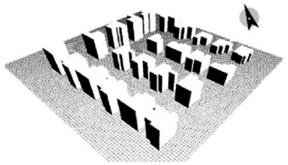
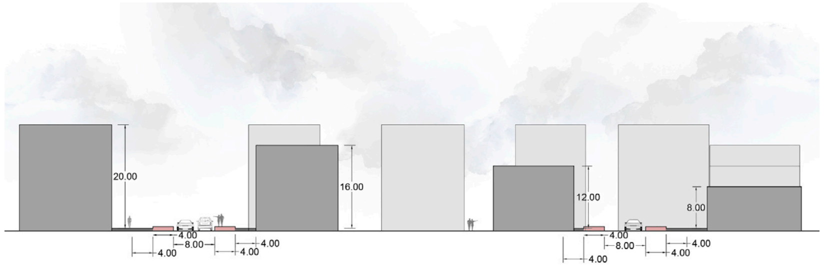
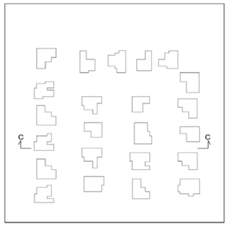
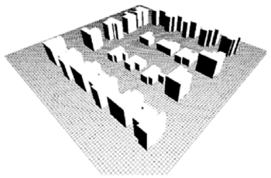
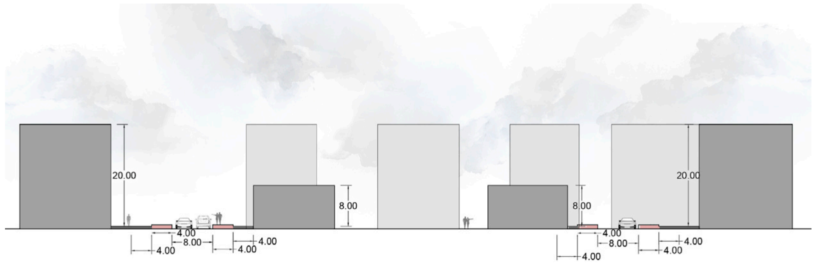
3D geometry		Urban geometry	Building height	Built-up area
	  D2 = 20:16:12:8 m A gradual decrease from the north-west direction		20:16:12:8 m	20,300 m^2
	  D3 = 20:8 m Courtyard effect		20:8 m	21,800 m^2

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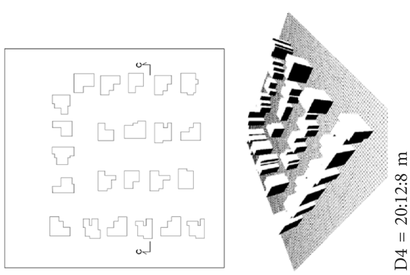
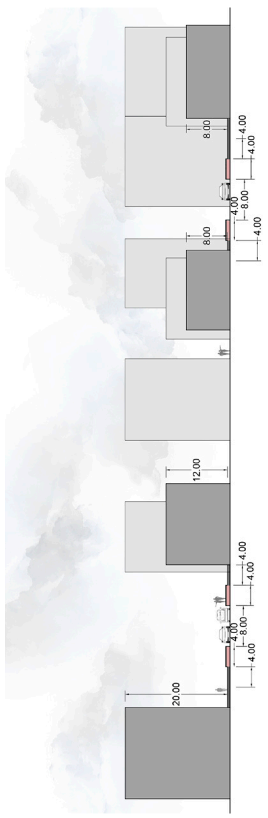
TABLE 5 (*Continued*) The second configuration group has diverse building heights.

3D geometry	Urban geometry	Building height	Built-up area
 D4 = 20:12:8 m Semi-courtyard effect from north-west and south directions		20:12:8 m	21,300 m²

maintain a cooler indoor temperature, while in the cooler winter months, the OUT_SET may be set higher to maintain a warmer indoor temperature. Moreover, the value of the OUT_SET in the UAE depends on other factors, such as the type of building, the intended use of the space, and the prevailing weather conditions. Typically, in the UAE, the OUT_SET for commercial buildings such as offices, malls, and hotels is set to around 24°C–26°C, while for residential buildings, it may be set slightly higher at around 26°C–28°C. However, these values may vary depending on the specific requirements of the building and the preferences of the occupants. Additionally, during the summer months when outdoor temperatures can exceed 40°C, the OUT_SET may be set lower to maintain a cooler indoor temperature and ensure the comfort of the occupants. Thus, designing urban areas with passive strategies and decreasing the outdoor temperature can help improve the OUT_SET temperature. Moreover, Nie et al. (2022) mentioned that one of the key elements influencing the quality of life and livability of outdoor space is outdoor thermal comfort, which has received significant attention in urban planning and architecture. Hence, a variety of thermal indicators, such as OUT SET and the universal thermal climate index (UTCI), have been developed globally to measure it.

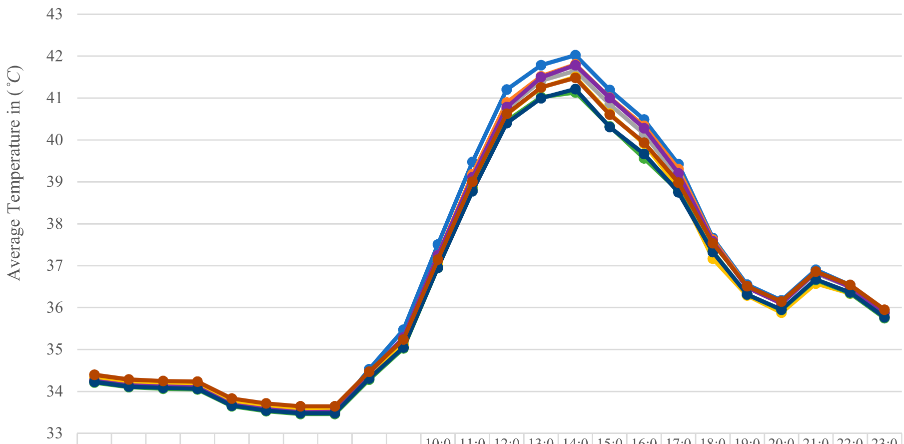
This research aimed to examine better thermal scenarios related to height variation in housing projects, which has rarely been discussed in previous research. Research on housing in hot arid climates such as the UAE was limited. This research is anticipated to assist in designing sustainable housing projects and fill the gap to improve the outdoor thermal conditions and thermal comfort for the users while also lessening the impact of the urban heat island.

2 Methodology

A qualitative examination method was used for this study based on a case study, ENVI-met software analysis, and descriptive analysis (Figure 2). This study's primary goal was to investigate the thermal effects of height variation on the urban design and canyon thermal performance of a housing complex in the hot arid climate of the United Arab Emirates as this topic has received little attention in prior studies. The study will assess the current thermal characteristics of the Sheikh Zayed Housing Programme (SZHP, 2023) as a case study, focusing primarily on the height of the structures, and then look at alternative height-to-width ratio solutions that could enhance the urban thermal characteristics and the users' thermal comfort. In this research, the thermal performance for the different configurations was measured by the related variations in the air temperature. The UTCI, which is used to assess the connections between the outside environment and people's well-being, was utilized to compute the predicted mean vote (PMV) for the solutions. The basic elements that influence how the human body feels while exposed to the environment include temperature, humidity, wind, and radiation (Littlefair, 2000). Finally, other methods and resources supported this study, such as data collection from journals, site visits, and municipality records.

2.1 Study's climate conditions

The study was conducted on a housing project (Figure 3A) in Ajman Emirate, UAE (Figure 3B). Average temperatures in Ajman



	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
B1	34.2	34.1	34.1	34.1	33.7	33.6	33.5	33.5	34.5	35.5	37.5	39.5	41.2	41.8	42	41.2	40.5	39.4	37.7	36.5	36.2	36.9	36.5	35.9
U1	34.3	34.2	34.1	34.1	33.7	33.6	33.5	33.5	34.4	35.3	37.2	39.2	40.9	41.5	41.8	41	40.3	39.3	37.6	36.5	36.1	36.9	36.5	35.9
U2	34.3	34.2	34.1	34.1	33.7	33.6	33.5	33.5	34.4	35.2	37.1	39.1	40.7	41.4	41.7	40.8	40.1	39.1	37.6	36.5	36.1	36.8	36.5	35.9
U3	34.3	34.2	34.2	34.2	33.8	33.7	33.6	33.6	34.4	35.1	37.1	38.9	40.6	41.2	41.5	40.6	39.9	38.9	37.2	36.3	35.9	36.6	36.3	35.8
D1	34.3	34.1	34.1	34.1	33.7	33.6	33.5	33.5	34.4	35.3	37.2	39.1	40.8	41.5	41.8	41	40.3	39.2	37.6	36.5	36.1	36.8	36.5	35.9
D2	34.2	34.1	34.1	34	33.6	33.5	33.5	33.5	34.3	35	36.9	38.8	40.5	41	41.1	40.3	39.6	38.8	37.3	36.3	35.9	36.7	36.3	35.7
D3	34.2	34.1	34.1	34.1	33.7	33.5	33.5	33.5	34.3	35.1	36.9	38.8	40.4	41	41.2	40.3	39.7	38.7	37.3	36.3	36	36.7	36.4	35.8
D4	34.4	34.3	34.2	34.2	33.8	33.7	33.6	33.6	34.5	35.2	37.1	39	40.6	41.3	41.5	40.6	39.9	39	37.5	36.5	36.1	36.9	36.5	35.9

FIGURE 5
Hourly average air temperature (˚C) for the base case and the two configuration groups.

can soar as high as 41˚C throughout the summer (Figure 3C) due to the region's hot and dry climate. Due to its proximity to the seaside, it is often more temperate than other emirates in the UAE. The winters are pleasant, with average lows of 22˚C. Ajman receives little rain on a yearly average, with the majority falling between December and March. The dominant wind in Ajman is the north-west wind (Figure 3D). Overall, Ajman has a desert climate distinguished by hot summers, moderate winters, and little precipitation.

2.2 Study software for the thermal analysis

A microclimate software program called ENVI-met was used to simulate thermal effects for the housing project case study. ENVI-met software is designed for use in many applications, including building design, urban planning, and climate change adaptation, for forecasting, analyzing, and visualizing the microclimate of cities, buildings, and green areas (ENVI-met 2023). With more than 3,000 independent studies, ENVI-met has been verified by a large number of researchers and practitioners, including in the urban climate and the urban microclimates (Salameh and Touqan, 2022; Salameh and Touqan, 2023; Wang et al., 2023; Alyakoob et al., 2023; Ghaffarianhoseini et al., 2015; Lee et al., 2016; Taleghani et al., 2014; Air Temperature, 2022; Forouzandeh, 2018).

The author conducted validation for the simulation using ENVI-met software on the same case study recorded in Salameh et al. (2022) as they used average measured air temperature data (Figure 4A) collected with an Extech meter (Figure 4B) from four points A, B, C, and D and compared those temperatures with their corresponding average air temperature data from the simulation using ENVI-met on 21 August 2020 (Figure 4C). The measured and simulated air temperature data were well correlated, as seen in Figure 4D. Despite some differences in the data sets, primarily due to the accuracy of the field measurement meter, the R^2 score was 0.85 (Salameh et al., 2022). For more validation for the ENVI-met simulation results, the root mean square error (RMSE), a commonly used index for evaluating the accuracy of a model or software (Bande et al., 2019), was implemented in this study based on actual and predicted values gathered by the authors in Salameh et al. (2022). RMSE measures the difference between predicted values and actual values and is calculated by taking the square root of the average of the squared differences between predicted and actual values. A lower RMSE value indicates better agreement between predicted and actual values. For this study, the RMSE = 0.62 C˚ (see Figure 4E) and is considered valid, as higher RMSE values up to the levels of 4.83 obtained by Song and Park (2015) and 3.35 obtained by López-Cabeza et al. (2018)were deemed valid.

2.3 Case study simulation analysis criteria

The research investigated the effect of the variation of the building heights in a housing project in the hot arid climate of the UAE on the outdoor thermal conditions in the related district. The investigation included two main parts: 1) The base case of the housing project plot (Table 1) and 2) the proposed scenarios for the height variations to be examined to identify the best configuration that can help in modifying the outdoor air (Table 2).

In the ENVI-met software application, the simulation plot area for the existing and proposed height configurations was in a

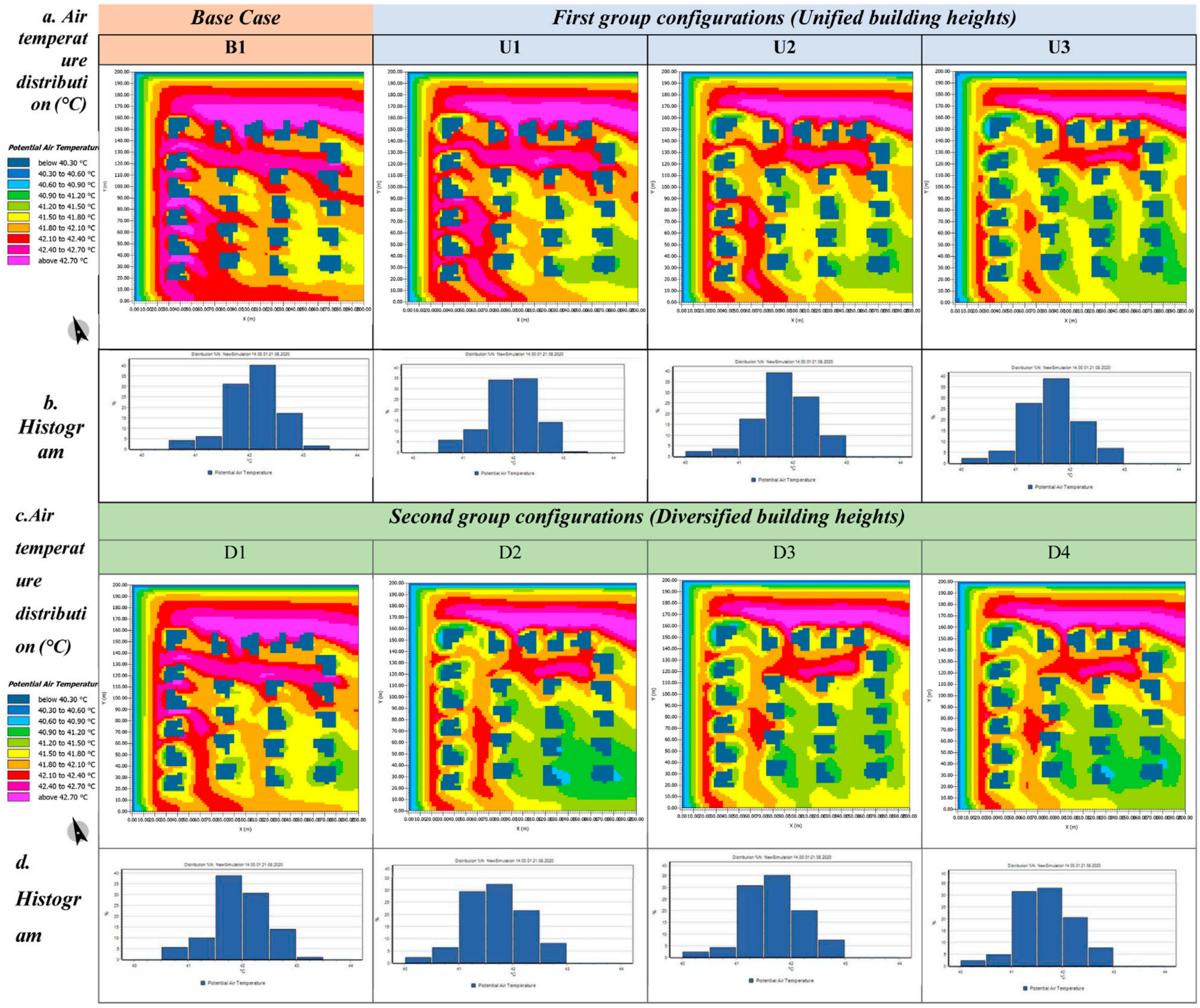


FIGURE 6
Air temperature distribution on 21 August at 2:00 p.m, **(A)** Air temperature distribution for base case and first group configurations, **(B)** Histogram for base case and first group configurations, **(C)** Air temperature distribution for second group configurations, **(D)** Histogram for second group configurations.

working space with an air volume of 200 × 200 × 50 m^3 and a height of 50 m for the air column based on a grid of 2 m in the x, y, and z directions (Table 3). These properties for the working space were considered fixed parameters for all the simulations of the different building height configurations for this research. The simulations were run for 36 h starting from 20 August at 6:00 p.m. until 21 August at 11:59 p.m. The extracted simulation data were for 21 August 2021. The selected site was simulated based on reality in terms of orientation, building materials (Table 3), built-up area, street geometries, street orientations, and 3D geometries. The date selected for the investigation was 21 August, the hottest month of the year in the UAE with an average high air temperature of around 41°C and an average low temperature of 34°C. These readings are above the thermal comfort defined by Khalfan and Sharples (2016), who claimed that the thermal comfort diagram is between 20°C and 27°C in accordance with Schnieders' thermal comfort diagram.

When comparing and evaluating the thermal characteristics of the existing and proposed configurations for the housing project using ENVI-met, a variety of metrics and variables were used. These metrics included the following:

1- The air temperature is a direct indicator of thermal performance in urban settings (Feroz, 2015).
2- Sky view factor (SVF), as it directly affects the sun exposure and the shadow index, thus the outdoor air temperature.
3- Thermal comfort is projected by the predicted mean vote (PMV), which predicts its values for thermal comfort outside.

The energy balance of user bodies within the fabricated microclimates is considered in PMV calculations. Using the ASHRAE scale, ENVI-met calculates PMV, with +3 meaning extremely hot weather and −3 denoting severely cold weather (Iowa

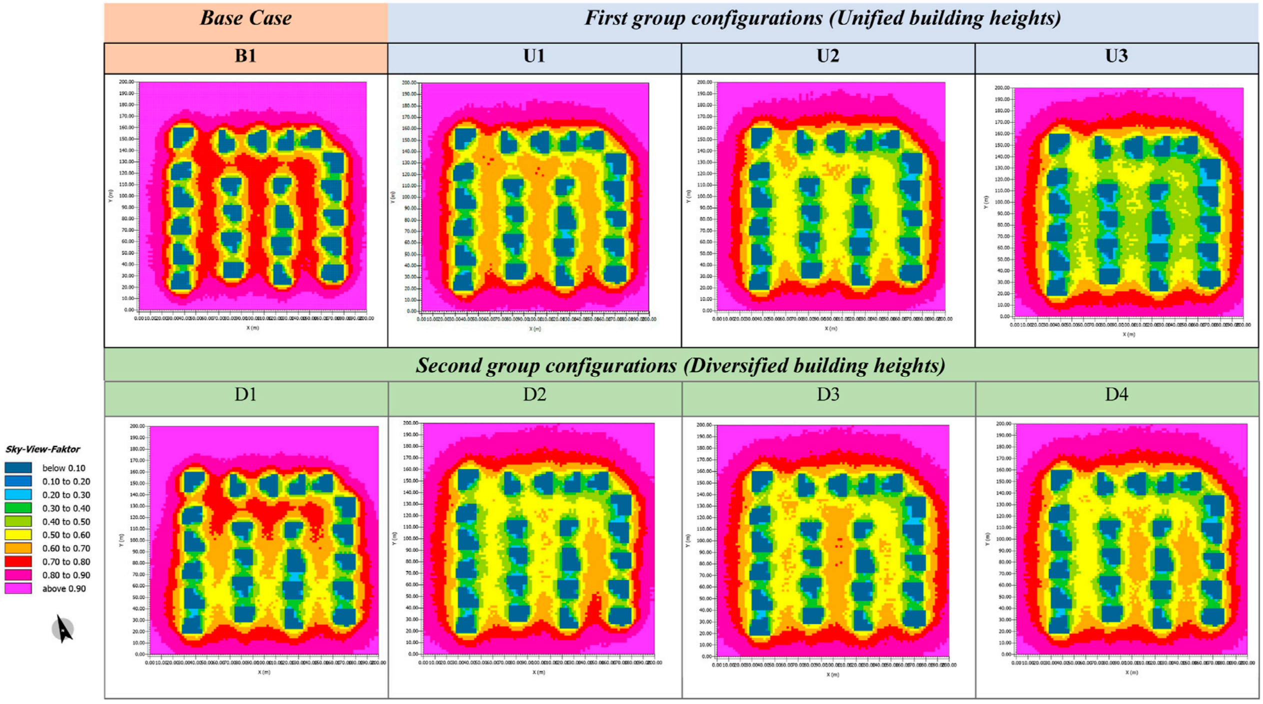
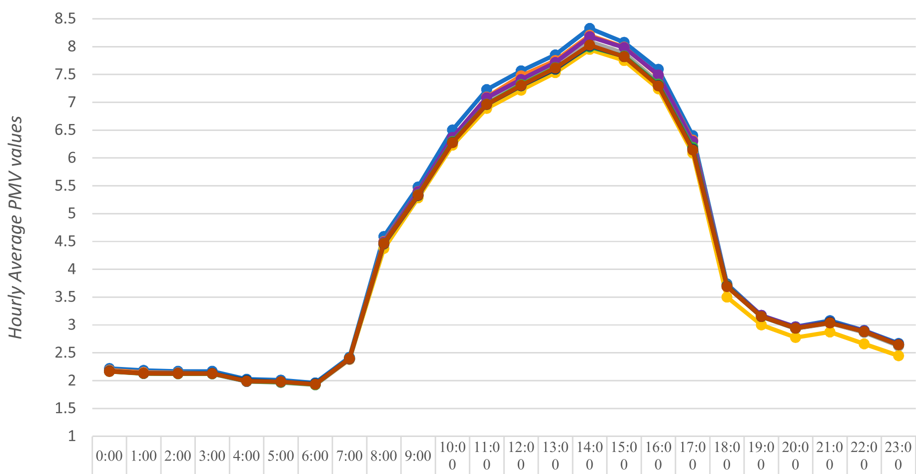


FIGURE 7
Sky view factor for the base case and the two group configurations (images generated by ENVI-met).



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B1	2.22	2.19	2.17	2.17	2.03	2.01	1.96	2.42	4.59	5.48	6.51	7.23	7.57	7.86	8.33	8.08	7.6	6.41	3.74	3.18	2.97	3.08	2.91	2.67
U1	2.19	2.15	2.14	2.14	2	1.98	1.94	2.4	4.5	5.4	6.36	7.1	7.48	7.75	8.21	8	7.48	6.32	3.71	3.16	2.94	3.04	2.87	2.63
U2	2.17	2.14	2.13	2.12	1.99	1.97	1.93	2.38	4.44	5.33	6.3	7.01	7.35	7.65	8.09	7.89	7.36	6.21	3.69	3.15	2.94	3.03	2.87	2.63
U3	2.17	2.14	2.13	2.13	2	1.98	1.94	2.39	4.38	5.29	6.23	6.89	7.22	7.54	7.95	7.75	7.25	6.09	3.5	3	2.78	2.88	2.66	2.45
D1	2.17	2.14	2.13	2.13	1.99	1.98	1.94	2.39	4.49	5.4	6.37	7.09	7.41	7.72	8.18	7.99	7.5	6.3	3.71	3.18	2.97	3.06	2.9	2.66
D2	2.17	2.13	2.13	2.13	1.99	1.98	1.93	2.4	4.47	5.34	6.3	6.97	7.32	7.63	8	7.84	7.33	6.2	3.71	3.16	2.95	3.05	2.89	2.65
D3	2.18	2.14	2.14	2.14	2.01	1.98	1.95	2.4	4.46	5.33	6.28	6.96	7.3	7.6	8.02	7.82	7.31	6.16	3.7	3.16	2.95	3.05	2.89	2.65
D4	2.17	2.14	2.13	2.13	2	1.98	1.94	2.4	4.47	5.34	6.28	6.97	7.31	7.62	8.03	7.82	7.3	6.15	3.69	3.16	2.95	3.04	2.89	2.65

FIGURE 8
Hourly average PMV values for the base case and the two configuration groups.

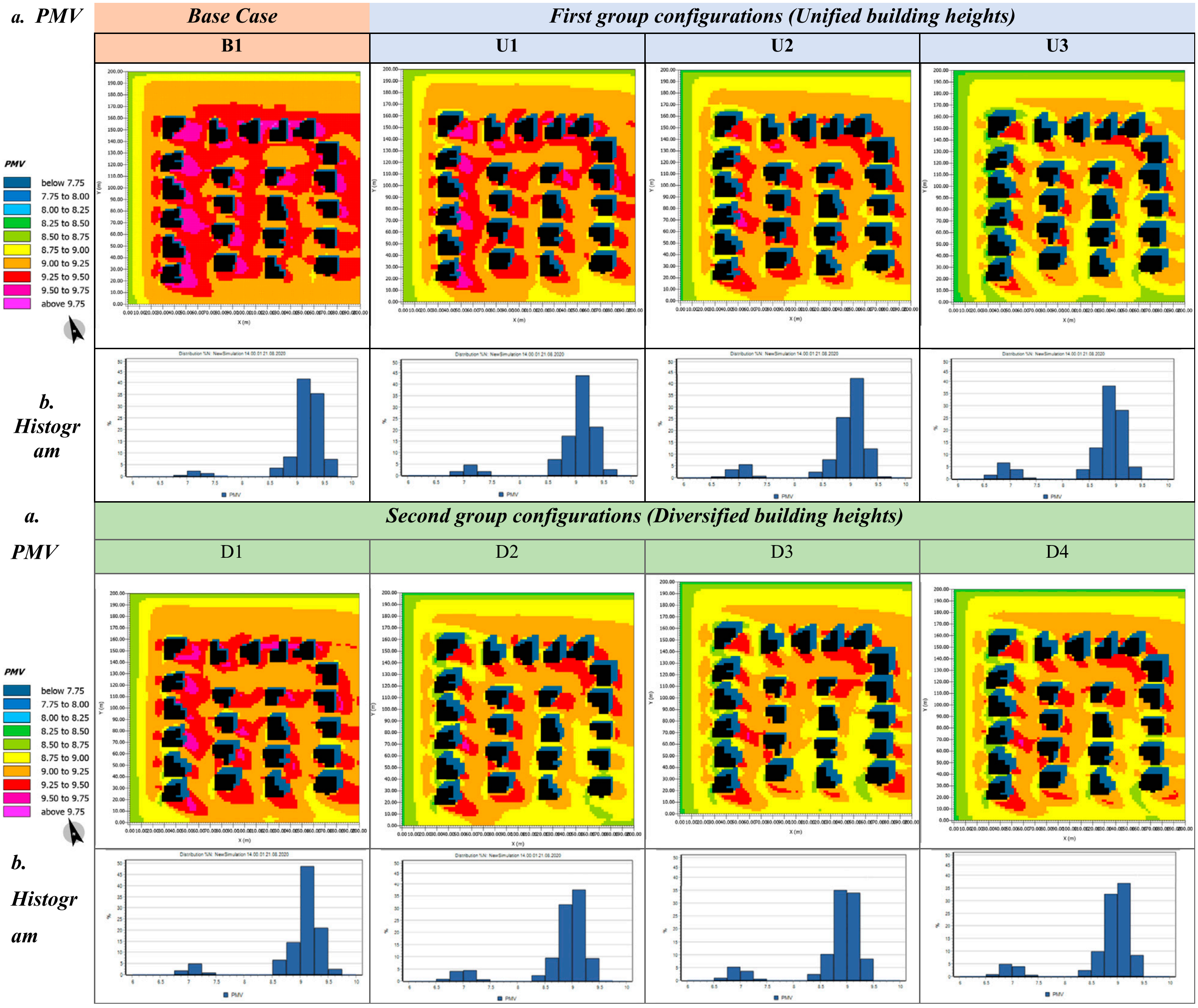


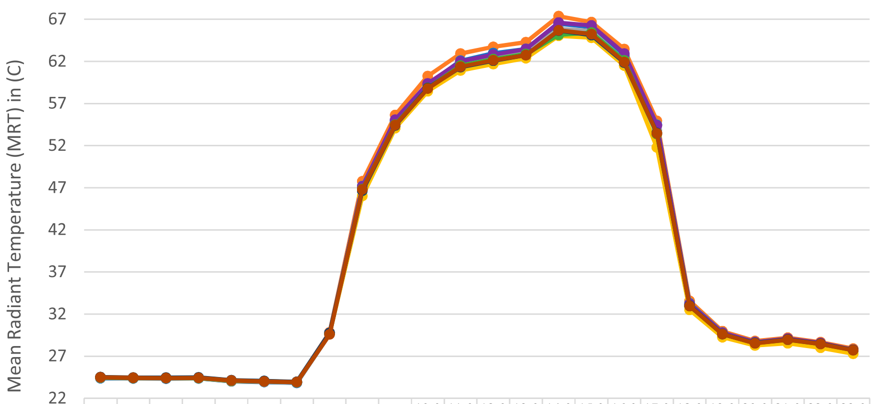
FIGURE 9
PMV results on 21 August at 2:00 p.m, **(A)** PMV results for base case and first group configurations, **(B)** Histogram for base case and first group configurations, **(C)** PMV results for second group configurations, **(D)** Histogram for second group configurations.

Environment Mesonet, 2023). Additionally, a broader scale for open-air temperatures was included, ranging from +4 (extreme heat) to −4 (extreme cold) (PMV-ENVI-met, 2021). PMV is frequently linked to other aspects of the human body, such as the user's age, metabolism, and gender, as well as external factors, including wind speed, humidity, air temperature, and radiant temperature (PMV-ENVI-met, 2021). Consequently, it has been established that a wide range of direct and indirect elements can affect thermal comfort; nonetheless, Lai et al. (2020) asserted that air temperature has a substantial impact on customers' thermal comfort.

The base case and the two proposed configurations have building heights that vary from 8, 12, and 16, to 20 m. The first configuration group has unified building heights. In the first configuration, U1 has a unified height of 12 m, the U2 configuration is 16 m, and U3 is 20 m, as shown in Table 4.

The second group of configurations has diverse building heights. The D1 configuration has a gradual height decrease from the south direction starting from 20 m and reaching the lowest height of 8 m, with the decrease following this pattern: 20, 16, 12, 8, and 8 m. The D2 configuration has a gradual height decrease from the north-west direction, starting at 20 m and reaching the lowest point of 8 m, following the pattern of 20, 16, 12, and 8 m. D3 has a courtyard effect, with 20-m buildings on the site boundary and 8-m buildings on the inside. Finally, D4 has a semi-courtyard effect, with 20-m building blocks facing the north-west and south directions, while the height gradually decreases inward to 12 m and 8 m, as shown in Table 5.

The H/W ratio increases with the increase of the building heights as does the built-up area. The urban configurations were simulated with fixed factors such as the UAE location, climatic data (arid and hot climate), building materials (default concrete wall with moderate insulation for walls and roofs, asphalt road, red stones for pedestrian paths and sidewalks, and loamy soil for unpaved areas).



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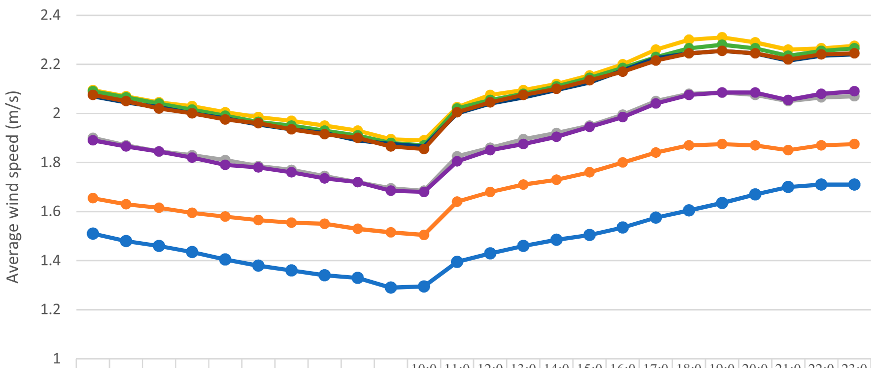
B1	24.5	24.5	24.4	24.5	24.1	24	23.9	29.8	47.8	55.6	60.3	62.9	63.7	64.3	67.4	66.7	63.5	54.9	33.6	30	28.8	29.2	28.7	27.9
U1	24.4	24.3	24.3	24.4	24	23.9	23.8	29.7	47.2	54.9	59.3	62.1	63	63.5	66.5	66.1	62.7	54.5	33.3	29.8	28.7	29	28.5	27.7
U2	24.4	24.4	24.4	24.4	24.1	24	23.9	29.6	46.6	54.4	58.9	61.6	62.4	63	65.9	65.6	62.1	53.8	33.1	29.7	28.6	28.9	28.4	27.7
U3	24.4	24.4	24.4	24.4	24.0	24.0	23.9	29.6	46.0	54.0	58.4	60.9	61.6	62.3	65.0	64.8	61.5	51.8	32.5	29.2	28.2	28.5	28.0	27.2
D1	24.4	24.4	24.4	24.4	24.0	24.0	23.9	29.7	47.1	55.0	59.4	62.0	62.8	63.4	66.6	66.2	62.9	54.4	33.2	29.7	28.6	29.0	28.5	27.7
D2	24.4	24.4	24.4	24.4	24.0	24.0	23.9	29.7	46.8	54.4	58.8	61.4	62.2	62.8	65.1	65.4	62.1	53.3	32.9	29.6	28.5	28.9	28.4	27.7
D3	24.5	24.4	24.4	24.4	24.1	24.0	23.9	29.7	46.6	54.3	58.8	61.3	62.0	62.7	65.6	65.1	61.8	53.5	33.0	29.6	28.5	28.9	28.4	27.7
D4	24.4	24.4	24.4	24.4	24.1	24.0	23.9	29.5	46.8	54.4	58.7	61.3	62.1	62.7	65.6	65.2	61.9	53.4	32.9	29.6	28.5	28.9	28.4	27.7

FIGURE 10
Hourly average mean radiant temperature (°C) for the base case and the two configuration groups.



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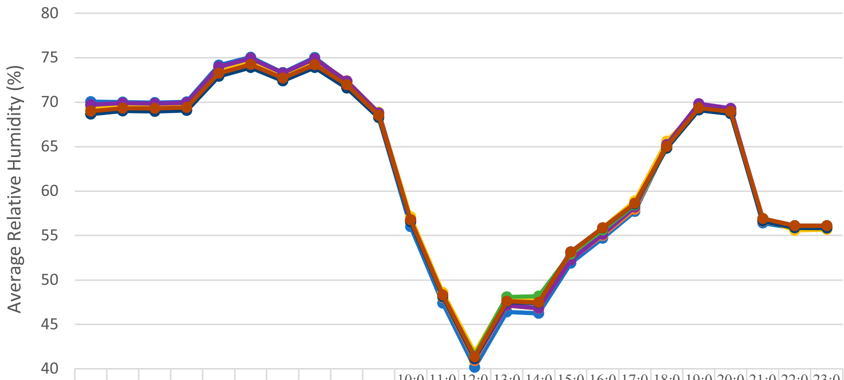
B1	1.51	1.48	1.46	1.44	1.41	1.38	1.36	1.34	1.33	1.29	1.3	1.4	1.43	1.46	1.49	1.51	1.54	1.58	1.61	1.64	1.67	1.7	1.71	1.71
U1	1.66	1.63	1.62	1.6	1.58	1.57	1.56	1.55	1.53	1.52	1.51	1.64	1.68	1.71	1.73	1.76	1.8	1.84	1.87	1.88	1.87	1.85	1.87	1.88
U2	1.9	1.87	1.85	1.83	1.81	1.79	1.77	1.75	1.72	1.7	1.69	1.83	1.86	1.9	1.92	1.95	2	2.05	2.08	2.09	2.08	2.05	2.07	2.07
U3	2.1	2.07	2.05	2.03	2.01	1.99	1.97	1.95	1.93	1.9	1.89	2.03	2.08	2.1	2.12	2.16	2.2	2.26	2.3	2.31	2.29	2.26	2.27	2.28
D1	1.89	1.87	1.85	1.82	1.79	1.78	1.76	1.74	1.72	1.69	1.68	1.81	1.85	1.88	1.91	1.95	1.99	2.04	2.08	2.09	2.09	2.06	2.08	2.09
D2	2.09	2.07	2.04	2.02	1.99	1.97	1.95	1.93	1.91	1.88	1.87	2.02	2.06	2.08	2.11	2.15	2.19	2.23	2.27	2.28	2.27	2.24	2.26	2.27
D3	2.07	2.05	2.03	2	1.98	1.96	1.94	1.92	1.89	1.88	1.87	2	2.04	2.07	2.1	2.13	2.18	2.23	2.25	2.26	2.25	2.22	2.24	2.24
D4	2.08	2.05	2.02	2	1.98	1.96	1.94	1.92	1.9	1.87	1.86	2.01	2.05	2.08	2.1	2.14	2.17	2.22	2.25	2.26	2.25	2.22	2.24	2.25

FIGURE 11
Hourly average wind speeds (m/s) for the base case and the two configuration groups.

The independent factors were building height, H/W ratio, SVF, and built-up area-to-plot area ratio. The simulation results, including outdoor potential air temperature, wind speed, relative humidity, mean radiant temperature, building average temperature, and PMV, are the dependent factors to identify the impact of each proposed configuration.

3 Results and discussion

A 200 m × 200 m plot was modeled and simulated using ENVI-met software on 21 August for the base scenario and the suggested two groups of height configurations for the houses. The findings of the simulation showed that the thermal performance varied amongst



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B1	70.1	70	69.9	70	74.2	75.1	73.3	75	72.3	68.3	56	47.4	40.2	46.4	46.2	51.9	54.7	57.7	65.1	69.6	69	56.4	55.8	55.9
U1	69.6	69.8	69.8	69.9	73.9	74.9	73.2	74.9	72.4	68.7	56.6	48	40.9	47.1	46.8	52.3	55	57.9	65.1	69.7	69.3	56.6	55.9	56
U2	69.5	69.7	69.7	69.8	73.7	74.7	73.1	74.7	72.3	68.9	56.9	48.3	41.2	47.3	47.1	52.6	55.3	58.4	65.1	69.6	69.2	56.9	56.1	56.1
U3	69.3	69.6	69.6	69.7	73.5	74.5	73	74.5	72.3	68.9	57.1	48.6	41.8	48	48	53	55.8	58.9	65.6	69.2	68.7	56.9	55.6	55.7
D1	69.7	69.9	69.8	69.9	74	74.9	73.3	74.9	72.4	68.8	56.8	48.2	41.1	47.2	46.8	52.3	55.1	58.2	65.2	69.8	69.3	56.6	56	56
D2	68.7	69	69	69.1	73	74	72.4	74	71.7	68.3	56.6	48.1	41.5	48.1	48.2	52.9	55.6	58.4	64.8	69.1	68.7	56.7	55.9	55.9
D3	68.7	69	69	69.1	72.9	73.9	72.4	73.9	71.6	68.3	56.6	48.1	41.1	47.5	47.4	53.2	55.8	58.5	64.8	69.1	68.7	56.7	55.9	55.8
D4	69	69.3	69.3	69.4	73.2	74.2	72.7	74.2	71.9	68.5	56.8	48.3	41.4	47.6	47.5	53.1	55.9	58.6	65	69.3	68.9	56.9	56.1	56.1

FIGURE 12
Hourly average relative humidity (%) for the base case and the two configuration groups.

the two height configurations, uniform and diverse, compared to the base case for the potential air temperature as in Figure 5, particularly at 2:00 p.m. during the peak hot hour (a time of high ambient air temperature and strong solar radiation). Looking at the first group of configurations with unified heights, U3 had the lowest average air temperature with a reading of 41.5°C, which is a reduction of about 0.5°C compared to the base case at 2:00 p.m., which recorded an average outdoor air temperature of 42.0°C. Note that U3 had a 0.83 H/W ratio for the streets, while the base case had only a 0.33 H/W ratio (Table 1); thus, the higher the H/W ratio, the better as a higher H/W ratio increases the shaded areas in the outdoor places and decreases the amount of the absorbed solar radiation.

In the second group with diverse heights, configuration D2, with the highest masses located to the north and west, had the lowest average air temperature with a reading of 41.1°C at 2:00 p.m., a reduction of about 0.9°C compared to the base case. D3 is the second-most thermally efficient configuration, with the lowest average air temperature of 41.2°C, a reduction of about 0.8°C compared to the base case.

Figure 6A shows the air temperature distribution on 21 August at 2:00 p.m. This figure confirmed that U3 from the unified height group had the best thermal performance based on the air temperature. U3, with uniform 20-m building heights for each mass, recorded the highest air temperature of 43°C for 7% of its cells. The base case recorded an air temperature of 43°C in 17% of its cells, and 2% of its cells recorded air temperature values of 43.5°C (Figure 6B). U3 performed the best of the unified group configurations because it has the highest masses (20 m), which created a small SVF that reduced the amount of solar radiation that reached the ground or masses of the urban district. In the base case, the masses reached only 8 m in height, which increased the SVF and allowed more solar radiation to hit the ground and the walls of the district (Figure 7). The SVF, which is measured from a certain place on the ground, is the proportion of the visible sky area to all viewable areas. In metropolitan locations, the amount of sky view can affect air temperature. Many studies have shown that lowering the SVF can lower daytime air temperatures, such as Svensson (2004), Unger (2004), Venhari et al. (2019), Ajman (2023), and Elkhazindar et al. (2022).

On the other hand, D2, with high masses located from north and west, had the lowest average air temperature of the two groups of configurations, as shown in Figure 6C. D2 configurations blocked the hot air that blew from the north-west, which helped reduce the air temperature in the district. D2 recorded the highest temperature of 43°C in 8% of its cells, while the base case had almost 17% of its cells at 43°C. In addition, the base case recorded higher air temperature values that reached 43.5°C in 2% of its cells, while D2 recorded lower air temperature values of 41.0°C in 2% of the area's cells. The lowest air temperature value for the base case was 41.5°C (Figure 6D). The good performance for D3 was mostly related to preventing the hot air from moving easily inside the housing plot. By restricting heat transfer from the hot air to the colder air around it, blocking hot air can enhance an area's thermal performance. Allowing hot air to move freely can cause heat to be transferred to nearby surfaces, which can subsequently radiate heat into the air, raising the ambient temperature.

The transfer of heat can be reduced, allowing the cooler air in the surrounding environment to maintain its temperature by blocking hot air. Minimizing the need for heating or cooling systems to counteract the impacts of hot air can boost a building or room's energy efficiency. According to Feroz (2015), the cooling impact of the wind circulation is insufficient in hot climates like Dubai.

D3 was ranked the second configuration in energy efficiency in the group of configurations with diverse heights. According to Figure 6D, D3 recorded the highest temperature of 43°C in 7.5% of its cells, compared to about 17% of the cells in the base scenario recording this temperature. Moreover, D3 recorded maximum air temperature values of 43.0°C, while the base case recorded higher maximum air temperature values of 43.5°C. The main factor in D3's successful performance was that this configuration mimicked the courtyard effect because it has high masses on the four borders that gradually lowered in height toward the center. This courtyard effect had high masses on the north-west side that blocked the hot air from moving freely inside the housing plot. Blocking the hot air improved the area's thermal performance by limiting the amount of heat transferred from the hot air to the cooler air surrounding it. The high masses on the south in D3 cast more shade inside the plot, which decreased the air temperature in the area. D3, in general, created a courtyard effect that improved the stack effect inside the plot and improved its thermal performance. As Al Raqaib (2021) mentioned, the courtyard forms have several attributes that enable them to work in a passive way to maximize the utilization of natural elements like sunshine and wind.

According to Detommaso et al. (2021), the ENVI-met Leonardo display heights increase by 0.4 m levels starting from 0.2 m, so the 1.8 m height was chosen to measure the PMV values as it was the closest to 1.75 m. This study used the standard PMV model developed based on Extech (2021) for a person aged 35, 1.75 m tall, weighing 75 kg, and walking at a speed of 4 kp. The PMV readings were identified according to that model's standards. In the PMV distribution shown in Figure 8, U3, a configuration with unified height, gave the best PMV among all the cases, with average values that ranged between 2.0 and 7.95, with the highest reading of 7.95 PMV at 2:00 p.m. For the base case, the average PMV values ranged between 2.03 and 8.33, with the highest PMV reading of 8.33 at 2:00 p.m. Figure 8 demonstrates that even though the distribution of the PMV for each case was higher than the desired range of −4 to +4 in the day time, the PMV for the U3 configuration succeeded in decreasing the average maximum PMV readings by 0.38 at 2:00 p.m. at the peak air temperature time compared to the base case. Therefore, it improved the thermal comfort in the district, which is clearly illustrated in Figure 9. This can be explained because U3 had the lowest values for the SVF; thus, it improved the thermal conditions in the outdoor areas compared to the other cases, which is in agreement with Venhari et al. (2019)and Elkhazindar et al. (2022), who mentioned that lower readings of SVF can improve users' thermal comfort.

D2, with high masses located on the north and west, had the lowest average air temperature compared to the two groups of configurations. The D2 had PMV average readings ranging from 1.99 to 8.00, which were lower than the readings for the base case average PMV values that ranged between 2.03 and 8.33 (Figures 8, 9). D3, with a courtyard effect, had the second-lowest average air temperature in the diverse-height group; PMV average values ranged between 2.01 and 8.02 and were also lower than the base case average PMV values.

The maximum mean radiant temperature (MRT) component of the universal thermal climate index (UTCI), in particular, had an effect on the PMV values for all occurrences. These components include mean radiant temperature, wind speed, and relative humidity. The MRT in the U3 configuration with the best PMV readings recorded MRT readings of around 65°C at 2:00 p.m., which is 2.4°C less than the base case. D2, which was second in thermal performance efficiency, recorded MRT readings of around 65.1°C, which is 2.3°C less than the base case (Figure 10).

The wind speeds for all cases are shown in Figure 11. The lowest average readings for the wind speed were for the base case, which recorded 1.49 m/s at 2:00 p.m., while the best case U3 followed by D2 recorded the highest values for the wind speed of 2.12 m/s and 2.11 m/s, respectively. These wind speeds are higher than the base case.

Figure 12 showed that the U3 configuration with the best PMV readings produced a relative humidity value of 48% at 2:00 p.m., which was greater than the basic case (46.2%), and the relative humidity for D2 was 48.2%.

It is evident that the MRT, relative humidity, and wind speed affected the PMV performance, as the best cases among the two groups of configurations, U3 and D2, had the highest readings of relative humidity and wind speed with the lowest readings for the MRT among all cases, including the base case.

4 Conclusion

This study's primary goal was to investigate the thermal effects of height variation in house structures on urban design and canyons in the hot, arid environment of the United Arab Emirates as this topic has received little attention in prior studies. The study assessed the current thermal characteristics of the Shaikh Zayed Housing Programme (SZHP), focusing primarily on the height of the structures, and then looked at alternative height variation solutions that can enhance the thermal characteristics and the users' thermal comfort.

The study revealed that building height plays a crucial role in the formation of the outdoor air temperature, thus the UHI phenomenon. After studying two configurations with unified and diverse building heights, the study found that the best case among the first group of configurations with unified heights was U3, which had unified mass heights of 20 m. U3 had the lowest average air temperature with a reading of 41.5°C (a reduction of about 0.5°C compared to the base case at 2:00 p.m., which recorded an average outdoor air temperature of 42.0°C). The higher masses created a higher H/W ratio and better thermal performance, as in the case of U3, which had a 0.83 H/W ratio with the lowest SVF for the streets, while the base case had only a 0.33 H/W ratio with the highest SVF. Moreover, the results revealed that in the case of diverse heights, it is better to locate the highest masses in the hot wind direction as in the D2 group, the highest masses with 20 m height were located only on the north and west sides of the area blocking the hot north-west prevailing wind. D2 had the lowest average air temperature reading of 41.1°C at 2:00 p.m., a reduction of about 0.9°C compared to the base case. In addition, it was revealed that the courtyard effect in the urban layout, as found in the D3 case, can help improve the thermal conditions for the area in general.

In the cases with lower air temperatures, U3 and D2 recorded the best PMV readings, especially in the daytime when the air temperature was high. It was clear that the MRT, relative humidity, and wind speed all had an impact on the PMV performance because the best cases, U3 and D2, had the highest relative humidity and wind speed readings and the lowest MRT readings among the other cases, including the base case.

Finally, it is recommended to decrease the SVF when possible in the housing districts to create more shade, and it is better to have higher H/W ratios for the streets. In cases where the housing project can have diverse heights, it is better to locate the highest masses in the direction of the hot prevailing wind. This will help improve thermal performance in the housing area, decrease the air temperature, and improve the PMV, which surely will help in reducing the effect of the UHI.

5 Study limitations

The study was only conducted at one location in the hot desert climate of the UAE. Future studies should consider additional housing projects to assess the advantages of height variation on the thermal performance of housing areas. In addition, because this study only looked at one summer day, it is advisable to investigate other days of the year to provide more comprehensive data.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

Author contributions

MS, AE, and BT: arrangement of the study idea, proposal, and writing. AE: software simulation. MS: imagery analysis, interpretation, and publication submission. BT: research supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Gain and pain: resilience of home mobility in early Shabiyat housing of Ras Al-Khaimah

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The Social Housing Program initiated by the United Arab Emirates Government in 1971 aimed to upgrade the living conditions of the local Emiratis. The early housing projects were later known as *Shabiyat*. Individuals living in harsh conditions in the mountains of Ras Al Khaimah were willingly and within a short period relocated to new houses an approximate distance from their original homes, and they had to adapt to the new lifestyle and place. Due to changes in these individuals' everyday practices, they questioned the resilience of their new houses. This study aimed to investigate the degree of resilience of the early Shabiyat housing and examine the notion of home mobility and how it is related to resilience through physical and nonphysical spatial transformation and everyday practice. The study is structured into two sections: first, understanding the resilience of the traditional settlements in the mountains; and second, examining the main characteristics of early *Shabiyat*, its main concept, and how it has addressed the Emirati society's needs. This will assist in tracing these structures' patterns of resilience and offer some practical guidance for professionals and the public in developing policies toward maximizing the sustainability of proposed future social housing projects.

KEYWORDS

social housing, resilience, spatial transformation, lifestyle, adaptation, mobile home

1 Introduction

Spatial transformation is one of the main themes of the United Arab Emirates' (UAE) modern history. "Now and then," "tradition and global," and "nostalgia and progress" were joined to form a new hybrid concept that became the main feature of the cityscape. Since the 1970s, local communities have strived for more satisfying spatial modalities reflecting the modern lifestyles rooted in their traditions and cultural values. This has resulted in hybrid spaces where modernity and tradition are in a continuous negotiation producing places that do not belong to either, where modernity, tradition, and resilience are in continuous debate.

This transformation in the UAE was initially caused by the increase in sales of petroleum and the emergence of the nation-state in 1971, resulting in vast changes in mobility patterns (Ahmed, 2011). One of the major projects during this period was the public housing program introduced to the UAE people as a gift from Zayed[1], their respected and beloved first sheik. This program aimed to offer good housing for all, wherever they were located. As a result, individuals experienced significant transformations that affected every aspect of their lives.

1 Al-Ittiḥād (1973), "Zayed's gift to the People," July 17, https://www.nla.ae

The housing program changed the way they lived, worked, and the places in which they stayed. For example, walkable informal neighborhoods were replaced with planned modern ones based on an orthogonal network to accommodate automobiles. The rise of the state created new work opportunities for the Emiratis, and the modern infrastructure allowed for more exposure to new ideas and forms to be integrated into the formation of their environment.

Since its initiation, the housing program has attempted to respond to the changing needs and lifestyle of the local community and their aspiration to join the global modern world. Many of these housing clusters have provided infrastructure and adequate services, including electricity and telecommunication services. Additionally, a mosque was built in each neighborhood, and open public spaces with shops for everyday requirements were included in the planning.

These public housing units have been repeatedly assessed to address and consider the community's needs in proposed housing units, and several limitations have been found[2]. The early houses were small in size and built for emergency cases to house as many individuals as possible. Additionally, concrete was used to build these houses, which has a relatively shorter life span than stone. Furthermore, no regular maintenance was conducted on these housing units.

Within this context, this study assessed the resilience of the early Shabiyat housing units and compared their resilience with traditional houses in the mountains. The assessment was conducted both in-person and virtually at different social, architectural, and urban levels.

2 Literature review

To deepen the understanding of the resilience of Shabiyat housing units, it is necessary to understand the process of spatial transformation of home mobility in its physical and nonphysical terms and its effects on new spatial lifestyles that have different degrees of confronting modernism. In his book "The Present Past," Huyssen (2003) identifies that it might be impossible to distinguish between the mythic past (the imagined one) and the real past (the existing one). This idea was also relevant to Sheshtawy (2019), who considered Sha'abi[3] houses a perfect medium through which to explore and unpack issues related to identity, encounters with modernism, and the practice of self-resilience in what he called a struggle between the past and present. It is an attempt to reconcile modernism and its legacy occurring in the politicization of memory. This debate opens the discussion regarding community resilience, including individuals' abilities to learn from experience, prepare, and cope with disturbances. However, Al Nakib (2016) posits that the rapid transformation of the urban landscape gave rise to a radically different lifestyle affecting everyday lives and resulting in a fragmented space (Limbert, 2010). Neher and Miola (2016) and Alawadi (2018) describes how individuals readapted and appropriated these spaces over time to meet their daily needs and routines. Cultural resilience is considered the capability of a cultural system (consisting of cultural processes in relevant communities) to absorb adversity, deal with change, and continue to develop (Folke, 2006; Thieli, 2016; Holtorf, 2018; Touqan, 2020).

Community resilience is an integral part of the United Nations (UN) 2030 Agenda, as well as the Council of Europe's mission[4]. It started from the concept of Heritage Community (Bokova, 2021) and was elaborated in the Council of Europe's Framework Convention on the Value of Cultural Heritage for Society.

The process of transformation and its effect on the resilience of Sha'abi houses can also be discussed through the transformation of mobile homes, where this transformation is caused by temporal and spatial changes, resulting in what is called home displacement. Constructing homes in displacement requires the critical reevaluation of the relationship between home and displacement from a spatial, material, and architectural perspective. Recent studies in the social sciences have examined how displacement created and reproduced homes under new conditions, thereby uncovering the contradictory positions of making a home and overcoming its loss, whether they are physical or nonphysical (Norris, 2020; Beeckmans et al., 2022). Cooke (2014) has used the term "tribal modern," reflecting his doubt regarding this transformation, which he called a clash between modernism and archaic ideas in the Gulf. He uses the term tribal modern to question whether tribal and modern can be intertwined or if they clash. The notion of displacement is also related to the nostalgia discourse, which affirms an authentic Emirati cultural identity, local rootedness, and separation from the foreign majority. Kanna (2011) has identified nostalgia for "the vanished village" as a key component of the "neo-orthodox" side of Emirati nationalism.

In the 1990s, mobility research started to translate the concept of lifestyles into "mobility styles" (Lanzendorf, 2002; Scheiner and Birgit, 2003; Götz and Ohnmacht, 2011); however, it is normally limited to modal choice. Scheiner and Birgit (2003) have focused on the interrelation between social structures (lifestyles, milieus), space–time structures, housing and choice of housing location, and daily mobility. They argue that spatial mobility was mainly based on spatial and individual restrictions. Neither the increasing degrees of freedom nor the subjective rationales behind mobility decisions were adequately considered (see Table 1).

This study contributes to previous literature reports by focusing on other dimensions of the physical and nonphysical transformation of Shabiyat housing and how this transformation, as a process and output, affects its resilience compared to the traditional settlements in the mountains.

3 Materials and methods

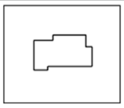
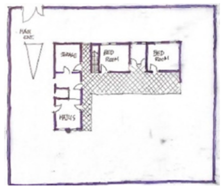
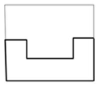
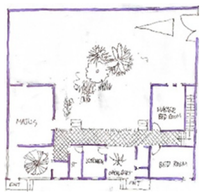
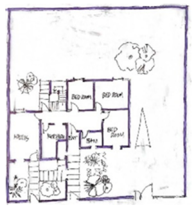
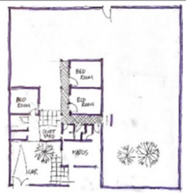
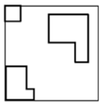
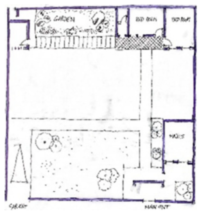
Resilience is the main topic of discussion in this study. The study is structured into three sections: first, understanding the

2 *Al-Ittiḥ;ād* (1973), "How is the construction of public housing proceeding?" July 16. https://www.nla.ae

3 Sha'abi is the singular of shabiyat, which is used as a collective.

4 Convention on the value of cultural heritage for society, 2005, Council of Europe, https://www.coe.int/en/web/culture-and-heritage/faro-convention

TABLE 1 Different typologies of Sha'abi houses that were implemented in the UAE in 1970–1990, source: Ministry of Public Housing, UAE.

			
Type 1: Centered: the house with its components situated in the center of the land plot surrounded by walls on all four sides. This type allows for different entrance locations but limits having one big open outdoor space.			
			
Type 2: Shift to side: the house is shifted to one side of the surrounding walls, leaving enough space for outdoor activities and future expansion.			
			
Type 3: Scattered: this type was one of the earliest types that followed the traditional plan by separating spaces of the house into private and public.			

indigenous settlement in the mountains of Ras Al Khaimah; second, understanding Shabiyat housing; and third, assessing the change in the resilience of the early social public housing provided to communities who were living in the mountains of Ras Al Khaimah. This study combined qualitative and ethnographic approaches, building on theories of spatial transformation and displacement to understand why and how individuals' new spatial lifestyle impacted the resilience of their houses. Using archive data from the National Archive Centre of Abu Dhabi, surveys and data on case studies and interviews with individuals were obtained to understand the context of Shabiyat housing and the living experience of its residents. In-depth interviews of residents with different backgrounds, including both men and women who used to live in the four selected areas, were also included.

Four case studies were selected to analyze the indigenous settlement in the mountains. Data were collected through several site visits, personal observation, and long interviews with people who used to live there. The study aimed to respond to the following questions:

Section 1: Understanding the indigenous houses in the mountains.

a. What is the typology of the houses regarding their plans, boundaries, shape, and materials?
b. What is the relationship of each house to the rest of the group?
c. What are the main sources of income?

Section 2: As per the selected model of 18 Sha'abi houses, the following questions were asked.

a. What is the main typology of the house regarding its
   i) location to the rest of the block,
   ii) relationship of different spaces within the house, and
   iii) architectural characteristic if it was inspired by tradition and materials?

Section 3: Focusing on the assessment of change in Sha'abi houses according to the following traits:

a. Physical transformation: Regarding spatial transformation in the Sha'abi house, what additions were made to the house, and what were the reasons for such changes?
b. Non-physical transformation: How did the transformations relate to the everyday practices and lifestyles of residents?

3.1 Living in the mountains

The top of the range of mountains in the Musandam Peninsula in Eastern Arabia constitutes a distinct geological, geographical, and ecological unit and has correspondingly

FIGURE 1
Image of wheat farms in the Alyanas area at the top of the mountains of Ras Al Khaimah.

more distinctive flora than has generally been recognized (Feulner, 2011). It is 1,500–2000 m of carbonate peaks and plateaus of the Musandam Peninsula. The mountains were inhabited by two tribes: Al Hubus and Alshehhi. Both tribes had lived in these mountains for a long time and had established a very resilient livelihood, enabling them to survive in harsh conditions with limited resources. The main concept for their resilience lay in their flexibility in adapting to the changing environment and their independence from outside resources as everything made was locally produced. They built stone houses from local materials attached to the mountain's edge to protect themselves and their animals from the cold winter weather. They minimized the exposure to the wind by building their houses without windows and half a meter under the ground level. The houses were covered with *Areesh* over palm fronds, and they left these houses in the summer to look for food for their animals. The people lived and moved in groups and supported each other through various jobs and duties. They formed very strong social groups based on their tribal structure. The houses were grouped together, sitting on the edge of a hill in a natural organic composition, and no clear boundary separated the village from its surroundings. Each house had an outside terrace with low stone walls defining the family's private space. Additionally, no particular walls surrounded the houses; however, each specific function had its own separate space (Figure 1).

These villagers' main income came from their goats, which provided milk and food throughout the year. Both men and women shared the work responsibilities of earning a living (Rashed, 2013). Women worked with pottery, gathered honey, and herded and milked the sheep twice a day, in the morning and the afternoon. Additionally, they baked bread and prepared food for the family.

Um Ali is a woman in her 70s and a mother of eight who had lived in the mountains before her family was offered a public housing unit in 1976. She said:

> Every day I used to wake up early in the morning to take care of the goats, make bread, bring water from wells in the mountains, and then work in pottery. I used to produce plates and cups and sell them for 2 AHD dirhams. It was a hard job, but I liked it. To make pottery, I had to collect clay and filter it and take the smooth particles and add water to produce a paste that I could work with (Figures 2A, B).

In Abdel Alrahman (2013), Abu Rashed described the old days in the mountains and the making of pottery. He said:

> Making pottery is really hard, and it is a locally excellent product: the material, the making, and the selling. It takes all day to produce it by collecting the materials, preparing them, molding them, and burning them in rocky furnaces. There used to be 40 furnaces scattered in the mountains, and their ruins are still there (Abdel Alrahman, 2013).

Furthermore, in Abdel Alrahman (2013), Thulab Ajab Almansori described animal farming in the mountains:

> Sheep was the most important wealth for the Emiratis. It is very useful. It provided them with food (milk and meat). Every person used to own tens of them and spent a lot of time protecting them from the wolves and wild animals in the mountains and moving from one place to another in search of water and food (Abdel Alrahman, 2013).

The analysis was conducted on four areas of indigenous settlements in the mountains. Alghazle and Alyanas are located at the top of the mountains, and Alhair and Bana are located down the valley. Alhair is located on the off-road to Oman. It is the site where most of the houses were demolished and deserted. The new Sha'abi was developed next to it. Some plots were newly surrounded with walls to define the property boundaries. Bana is a group of round, terraced houses down the mountain. The spaces of the house are separated and have different functions; sleeping rooms are located on the upper terrace, and the

FIGURE 2
(A) Indigenous house groups in the Bana area **(B)** Um Ali, who used to live in the indigenous houses of the Bana area, talking about her memories.

service and storage sections are located on the lower level. Al Ghazleh is a village located at the top of the mountains looking over the wheat fields. Horizontal plains were created to take advantage of the rainwater passing from higher areas. The terraced stone houses are grouped around a wheat field. Alyanas is a village at the top of the mountain where the wheat fields are located. It is relatively larger than other villages and comprises separated wheat farms, following the topography of the land. Every field is surrounded by a group of houses, and the residents thereof are responsible for wheat farming. Most of the houses are rectangular in shape.

3.2 History of early Shabiyat housing

In the 1970s, the founder of the UAE, Sheikh Zayed Al Nahyan, initiated a housing program[5] aimed at offering decent housing for low-income families living in either temporary accommodations or harsh environmental conditions, such as individuals living in the mountains (Maclean, 2016). The program, funded by the federal government, is still running and provides different options to all UAE citizens. In Ras Al Khaimah, a new planned area of medium size and equal plots was designed to have the same types of housing plans scattered in the different regions according to the relative proximity of their locations. The individuals living in the mountains were given units in the valley, while the individuals living in the desert were given units inland or near the sea.

The early Shabiyat in Ras al-Khaimah was implemented in 1973. According to the "Alithad" newspaper, 520 houses were built in the inland villages and mountains. Of these, 120 houses were for the Alhubus families who lived in the mountains of Ras Al-Khaimah, another 40 housing units were provided in the Shamel area near the sea, and 20 housing units were provided in Albrairat down the mountains. Each house was approximately 90 square meters in area and comprised two bedrooms, a majlis[6] (a sitting room), a kitchen, and services. The aim was to provide a healthy environment for all Emiratis, wherever they were, as a gift from Sheik Zayed (Tables 1, 2).

According to statistics compiled by the Ministry of Public Works, the program started with small-sized housing units of approximately 108 square meters, including two bedrooms and a majlis on a plot size of 900 square meters. In the 1990s, these units were enlarged to a two-floor housing plan of 367 square meters on a plot size of 1,620 square meters, with four bedrooms, a living room, and a majlis (Ahmed, 2011).

The housing units proposed by the government were divided into three broad categories: free ready-made housing units for groups of low-income citizens, houses built by the owner through financial grants with plots of land suitable for building private accommodation (such grants were also available for nationals who wished to expand their existing living area), and long-term (up to 25 years), nearly interest-free, loans offered to citizens with the financial capability to repay them.

Different models of housing units were implemented in different areas. The main idea remained the same: a design solution that addressed the cultural values of the community and integrated their needs into the plans and layout. Some of these considerations were to have a large outdoor area in each plot to allow for future extension and possible additions. The spaces of each house were organized according to their function and level of privacy. The majlis was located near the main entrance, the kitchen and service areas were separated from the bedrooms, and a shaded area linked all spaces together similarly to a traditional liwan[7] (entry hall). Additionally, a staircase led to the roof, which provided seating during the

5 Ministry of Public Works and Housing, UAE (1988) Dawr wizaret alashgal wa eskan fi altanmya (1988).

6 Majlis is a guest room for men that usually has its own entrance. Most of the time, it is separated from the rest of the house for privacy.

7 *Al-Ittiḥ;ād* (1973), "Houses for the People," July 15; and *Al-Ittiḥ;ād* (1973), "Zayed's Gift to the People," July 17.

TABLE 2 Different relationships of spaces in a Sha'abi house according to the typology explained in Table 1.

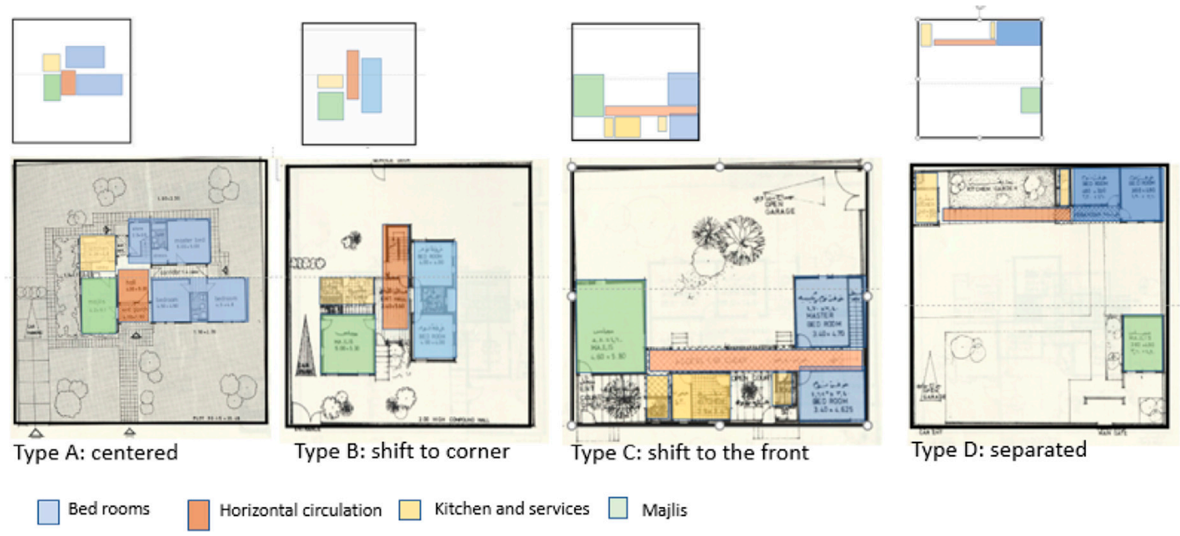


FIGURE 3
(A) Areal image of the Alhair area where Sha'abi houses were built next to indigenous houses **(B)** A few shops are located on one side of the Alhair Sha'abi house close to the main road.

hot summers. Some architectural elements were used for aesthetics, such as a hollow-block screen separating the outside from the inside and allowing more privacy. These houses were designed to accommodate changes and become an expression of their residents' culture and new lifestyle.

4 Results

According to an interview with Mr. Ahmed Alabdoli, the vice president of the Ministry of Housing, the early housing model was an attempt to meet local needs by integrating traditional settings into the new proposed plans. Privacy was considered in many ways: two entrances were allocated for each house, one for the family and the other for the guests; an open area was provided for outdoor activities and to allow for future expansion; a shaded area was provided at the back of the house to reduce the heat of the sun on the exterior wall of the houses; and a staircase led to the roof to offer a space for sitting during summer[8] (Figures 3A, B).

4.1 Physical transformation

The layout of the stone houses was naturally clustered in groups of houses in various distributions. Some stone mountain houses were clustered on a hill far away from rainwater, and others surrounded the wheat fields. The boundaries of each house were very simple and comprised half-meter-high stone walls.

The houses the villagers used to live in were also an example of resilience, allowing them to overcome the harsh climate, cold winters,

8 Itihad newspaper, page 3 July 1973.

TABLE 3 Different selected areas of indigenous mountain villages. Column A: Taken from Google Earth, the images show the location of indigenous houses in relation to the Sha'abi houses and how they are grouped. Column B: Images show the current condition of the houses, as shown from Google Earth. Column C: The most common plan found in the indigenous settlement.

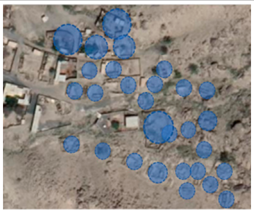
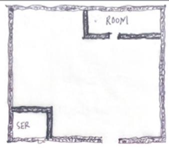
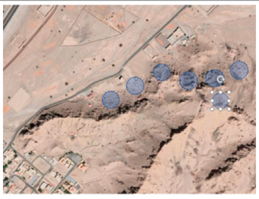
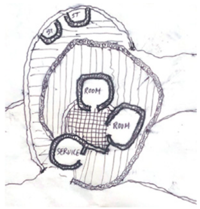
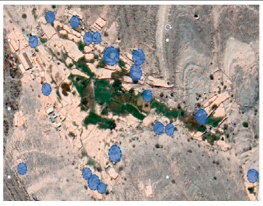
Name of the area	A	B	C
Al Hair			
Bana			
Al Ghazleh			
Al Yanas			

TABLE 4 Analysis of the indigenous mountain villages in terms of location, source of income, boundaries of the house and villages, shape of the house, and construction materials.

	Name of the area	Location	Source of income	House boundaries	Village boundaries	House plan shape	Materials
1	Al Hair	Down the hill	Palm and animal farming	Low stone wall surrounding the spaces of the houses	Do not exist	Circular	Stone and palm fronds
2	Bana	Down the hill	Palm and animal farming	Low stone wall surrounding the spaces of the houses	Do not exist	Rectangular	Stone and palm fronds
3	Al Ghazla	Up the mountain	Wheat and animal farming, and honey hunting	Do not exist	Low stone wall surrounding the wheat field and houses	Rectangular	Stone and palm fronds
4	Alyanis	Up the mountain	Wheat and animal farming, and honey hunting	Do not exist	Low stone wall surrounding the wheat field and houses	Rectangular	Stone and palm fronds

and hot summers. The houses had separate spaces located on different terraces, one for the residents and a different terrace for their animals. These simple houses were built in rectangular and circular layouts, with one or two stepping terraces with different levels of privacy. Their own space was embedded in the mountains, covered with palm trunks and areesh (a wooden structure made from palm fronds). One traditional type of house, used only in the mountains, is called an "alkifl" or a "cave." This type of house was sunk 1 m below the ground level of the front terrace, looking over the steep hills. The height of the roof of these houses was as low as 2 m to keep its inhabitants warm.

Additionally, these houses had no windows and could only be entered from one small door (see Tables 3, 4).

Although a thoughtful attempt to consider cultural issues was implemented in the design of the early Shabiyat, they were not fully accepted by the residents as the new houses were built with concrete, bricks, and unfamiliar materials.

In this respect, when the residents were asked about their new houses, their feedback mainly focused on the construction system, based on block walls, a system considered unsuitable for today's standards. The residents preferred beams and columns. They were also in favor of the high rooms or high exterior walls as they did not provide complete privacy. The residents' feedback was considered in future housing plans regarding space, organization, and structural systems[9].

However, the absence of regular maintenance of the Shabiyat negatively impacted its resilience. This was why almost 90% of the old Sha'abi houses, built in the 1970s, needed replacement, according to Mr. Fahed Abdel Aziz[10]the replacement of the house will be replaced if it is no longer good enough for living, there is no fixed time. Individuals either left their Sha'abi houses and built new rooms attached to them, or they conducted some minor maintenance to minimize the danger of the deteriorating materials[11]. This issue of a lack of maintenance has been covered several times in recent media[12]. Alrams' digital forum mentioned that Sha'abi houses either needed serious maintenance or should be replaced by new ones[13].

In May 2017, the Ministry of Public Housing issued an Memorandum of Understanding (MOU) with consultants entitling every resident of Sha'abi houses built before 1990 a grant to either demolish their housing unit and rebuild it or to do maintenance if the structural system was stable and safe enough[14].

Several changes were recently made to the early Shabiyat. Some houses were deserted as the residents left them for larger accommodations and more contemporary ones with two floors. Others were extended with many additions to the point where the original features were no longer recognizable. Some of the outdoor areas were replaced by other rooms to accommodate additional family members. The space in front of some housing units was covered by temporary materials and used as vehicle parking spaces. Several houses were inhabited by laborers, dividing them into small units using inadequate materials (Figures 4A, B).

9 Albayan newspaper, October 2022. https://www.emaratalyoum.com/local-section/other/2017-05-18-1.996565

10 Albayan newspaper, October 2022. https://www.emaratalyoum.com/local-section/other/2017-05-18-1.996565

11 Al Khaleeg newspaper, column by Hassa Saif, 21 March 2021. https://www.alkhaleej.ae/2021-03-28/

12 Needs pavement, especially the secondary roads, of Shabiyat houses, Alrams, 21 July 2016. https://www.alrams.net/35595

13 Emartat newspaper, 18 May 2017. https://www.emaratalyoum.com/local-section/other/2017-05-18-1.996565

14 An old woman who used to work in honey hunting said, "We use honey as money."

4.2 Nonphysical transformation

Although the places to which they were relocated were not far from their original residences, the residents' feelings changed tremendously as they felt that "something was missing." With modern conveniences of electricity, water, and paved streets to commute more widely and easily, the boundaries of their territories became small and undefined in contrast to their previous ones. These conditions have changed the meaning that residents attach to their houses and how they interact with each other and nature[15].

Often their attachment to their houses in the mountain made them return to them as a retreat or summer house. The Emiratis realized that to live and integrate into this modern world, they had to compromise with their past.

Um Ali, a woman in her 80s who used to live in the mountains, said:

> *I like it there up in the mountains. I have nice memories. I spent my entire life there doing pottery, feeding the sheep, and making bread for the family. Now, I am tired, I cannot go there even if I want to. Life is difficult there. Here, life is very easy.*

The old stone houses were kept alive in the hearts and memories of the Emiratis. This past is part of their cultural identity, and it gave them strength and steadiness; furthermore, it is on this land where honey became money.[16] Therefore, the residents decided to keep it alive through different modes and patterns; instead of perceiving the mountain as their source of income, it became their source of pleasure and joy. The Emiratis returned to the mountains and built their summer houses over or near their old houses. They even used the same old stones used to build their traditional houses. They integrated new construction techniques by using concrete in roofing and as a joining material between the stone courses. Furthermore, they respected the topography of the site and kept using terraces, similar to before, to define their different levels of privacy and territory. Now, they can face the future (Figure 5).

5 Discussion

There are two old Emirati sayings:

> *"Afsil behi aw ansil behi" and" Qallel wa Ammer."*

> The first meaning is "in your youth, you have to grow trees or have kids." The second meaning is "*save to live more.*"

These two sayings are familiar to the people who have lived in the mountains. The sayings indicate how resilient their communities were and how they managed to survive in the

15 *Al-Ittiḥ;ād* (1973), "All the services . . . are for the Bedouins," Jan. 30; *Al-Ittiḥ;ād* (1973), "How is the construction of public housing proceeding?" July 16.

16 Ittihad newspaper, page 3, 6 September 1981.

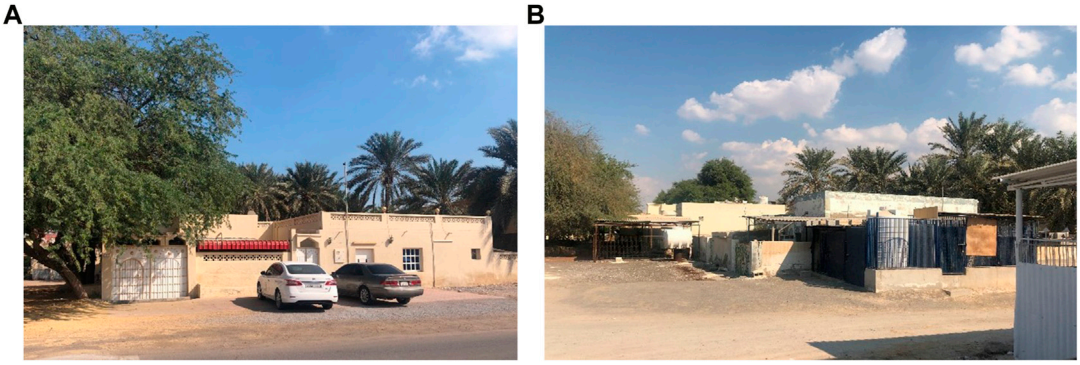


FIGURE 4
(A,B) Transformation of a Sha'abi house in Ras Al Khaimah shows its physical deterioration and many additions to the original layout of the house.

FIGURE 5
One of the new houses constructed on the top of the mountain replacing the indigenous settlement.

extreme conditions through their everyday practices. For many years before modernity invaded the Gulf, local communities in the mountains were thriving even though their lives were hard. Their indigenous culture taught them how to build their own houses, earn a living, and interact with each other and other communities.

Change is a crucial factor in assessing resilience. The UAE public housing, based on the relocation of the Emirati families, caused many changes due to their spatial proximity. Although local communities who used to live in the mountains were continuously moving during the year, their mobility was part of their traditional cultural system, ensuring their survival. In winter, they climbed up to their stone houses to look after their wheat farms in the stepped terraces called "Alwoob," a traditional setting to plant wheat in the mountains, taking advantage of the fertile soil carried by rain. In summer, they returned to the mountains to harvest their fields and store the produce and sell the surplus. When the housing program was initiated in the 1970s, these individuals were relocated into the valley in clusters of 20–50 housing units[17].

Physical and non-physical changes in the new environment were identified in this study. The physical changes included the architecture of the houses, their design, materials used, construction techniques, and layout. The nonphysical changes were identified through place attachment and the residents refusing or accepting the new houses.

The rapid transformation of the UAE's urban landscape gave rise to a new meaning of place attachment and its nonphysical resilience. New concrete masses consisting of single-family houses intruded into the natural landscape in most of the UAE region. It was difficult for the local community to leave their original settlements as they were strongly attached and had strong memories of their lives there[18]; furthermore, they considered their original settlements as part of their identity that transmitted their memories to the next generation. Moreover, they had no attachment to their new Shabiyat houses. After they moved into Shabiyat houses, they were informed that these houses were temporary and that they would later leave them for better ones. For this reason, the residents did not have an issue with leaving the new houses or even demolishing them to be replaced with new ones (Figures 6A, B).

The examples of mountain stone houses in Ras al-Khaimah are evidence of how the local people survived in the harsh mountain environment and were able to produce very authentic, resilient places in which they could transform nature from being their main challenge into an income resource. At the top of the mountains, local Emiratis planted and grew wheat on the stepped terraces, taking advantage of the winter rainwater to irrigate the field. Rainwater was also collected in man-made pools for their needs in summer. Wheat

17 Alrams, 21 July 2016. https://www.alrams.net/35595

18 Liwan is a semi open space located in front of the rooms looking over the open court house

FIGURE 6
(A) Abu Salem, resident of an Alhair Sha'abi house. **(B)** Um Ali and her neighbor sitting in the new Sha'abi house.

as a product became one of the sources of income where the efficient social system contributed to making it successful. Every individual had their duties, either irrigating the field, grinding the wheat, storing it in rocky silos, or selling the surplus to others. Other sources of income were honey gathering, pottery making, salt fish producing, and animal farming. This is a profound example of human adjustment to nature.

Early Shabiyat residential structures showed tendencies to be less resilient than traditional authentic settlements, where both physical and social resilience had profound influences in sustaining the structures. Shabiyat are considered transitional model houses, lacking the physical stability and social maturity to reach a resilient state.

An Emirati noted, "You must understand that our history is a history of gain and pain." His point was that "traditional" or "authentic" Emirati identity was important in light of the country's rapid development and the accompanying worldwide immigration of expatriates. Shabiyat housing units can be seen as a subjective field of memory and loss, where homes are a primary site of social resilience. The nostalgia discourse affirms an authentic Emirati cultural identity, local rootedness, and nostalgia for the mountain villages as a key component of the built environment's resilience.

This study concludes that the resilience of old houses in the mountains is based more on their physical than nonphysical qualities. Social resilience is another dimension that indicates how structures can face any changes if strong attachments are formed. The challenges of home relocation and mobility cause a critical reevaluation of the relationship between home and displacement from a spatial, material, and architectural perspective. It is a spatial practice that intrinsically relates to the production of the built environment.

Further studies are recommended to find tools that can increase the resilience of Sha'abi houses. Research should further focus on the diversity of discipline by integrating human behavior with the collective memory of a place. There are some limitations to this study; the inconsistency and continuous changing of the Sha'abi program hindered our ability to trace the direction of resilience and whether it is going in the right direction.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any identifiable images or data included in this article.

Author contributions

The author confirms being the sole contributor to this work and has approved it for publication.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Sustainable urban forms in the Arabian Gulf: an evidence-based analysis of Kuwaiti social housing neighborhoods at Jaber Al-Ahmed City

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In September 2015, the State of Kuwait signed the UN's 2030 Agenda, committing to all 17 of its Sustainable Development Goals (SDGs), which include the building of sustainable cities and communities through initiatives such as social housing. In response, the New Kuwait Vision 2035 has witnessed a shift in approach to the social housing paradigm at the state level. This paper examines the status of recent social housing projects in Jaber Al-Ahmed City, Kuwait, through a critical, evidence-based analysis of the decision-making processes and urban-architectural products that shaped its development. The mixed-methods data for this case study were generated via archival research and semi-structured interviews supplemented with field observations to evaluate the local and international sustainability agendas implemented in the city as process and product. Principles of Sustainable Urban Forms are implemented for the evaluation. The article also presents evidence of local urban practices (resident appropriation and participation), legitimized environmental practices, and community wellbeing. It concludes with recommendations for resolving issues in the current processes around the design and implementation of sustainable urban forms to inform future social housing developments. These recommendations for sustainable social housing in Kuwait provide an opportunity to revisit and reconsider the core values of sustainability while adding to the multiplicity of its definitions. Although recent social housing projects in Kuwait may demonstrate an overall effective process-to-product procedure as a means of architectural production that addresses the country's housing demand, important aspects remain in question with regard to sustainable built environments.

KEYWORDS

evidence-based, process to product, social housing development, sustainable social housing, sustainable urban forms, Jaber Al-Ahmed City, Kuwait

1 Introduction

In December 2012, at the United Nations (UN) Climate Change Conference in Doha, Kuwait announced its commitment to diversifying its energy sources by exploring its solar and wind capabilities, committing to an increase in its use of renewables to 1% of total energy consumption by 2015 and 15% by 2030. Building on this initiative, Kuwait endorsed and committed to all 17 of the UN's 2030 Sustainable Development Goals (SDGs) in September

2015, including SDG 11: Sustainable Cities and Communities. This SDG entails a commitment to "make cities and human settlements inclusive, safe, resilient and sustainable" (United Nations, 2015; General Secretariat of the Supreme Council for Planning and Development, 2019, p. 67). Accordingly, the government formed the National Sustainable Development Committee (NSDC) and the National Observatory of Sustainable Development (NOSD). It also tasked the General Secretariat of the Supreme Council for Planning and Development (GSSCPD) with drafting the third Kuwait National Development Plan (KNDP) to align with the New Kuwait Vision 2035 (General Secretariat of the Supreme Council for Planning and Development, 2020). The KNDP aims to "transform Kuwait into a financial, cultural, and institutional leader in the region" (Al-Sharhan, 2017). Kuwait's Vision 2035 set forth seven pillars based on the 17 SDGs, including Pillar 5: A Sustainable Living Environment, which "aims at ensuring the availability of living accommodation through environmentally sound resources and tactics" (General Secretariat of the Supreme Council for Planning and Development, 2019, p. 18). The Kuwait Voluntary National Review (VNR) to the UN (2019) records that the Public Authority for Housing Welfare (PAHW) participated in the steering committee for this process. However, the VNR provided very limited information about the housing outlook beyond the 2016 data showing the completed number of units (26,874 plots and 26,308 houses) and those being prepared or under construction (17,234 plots and 3,676 houses). These decisions have enabled Kuwait to consolidate a "sustainable" approach to social housing, although previous social housing initiatives did not adhere to any particular aspect of sustainability.

1.1 Regional sustainability and sustainable urban forms: A literature review

There has been minimal research into sustainable urban forms (SUFs) and sustainable social housing in the Arabian Gulf, and Kuwait in particular. Within the general discourse on sustainability and urban forms that emerged in the late 1990s (Frey, 1999; Jenks, 2000; Williams et al., 2000), a new theoretical framework for restructuring and understanding the form of sustainable cities was proposed in 2006 by urban planning scholar Yosef Rafeq Jabareen. Loosely described as the achievement of sustainable urbanism through the configuration of the functions, shape, and resiliency of city form (Ahmed, 2017; Mobaraki and Vehbi, 2022), the SUF concept merges four known urban forms with combinations of sustainable design concepts that define the sustainable city in terms of its social, economic and environmental aspects. According to Jabareen, these sustainable urban forms are neo-traditional development, urban containment, the compact city, and the eco-city. They are achieved by operationalizing seven design concepts: compactness, sustainable transport, density, mixed land use, diversity, passive solar design, and greening (Jabareen, 2006). The author's proposal aimed to establish a reliable "sustainable urban form matrix" to aid the evaluation of city form.

In 2017, Mohammed Galal Ahmed adopted Jabareen's framework to evaluate SUFs in Emirati social housing located in Al Ain City, United Arab Emirates. Ahmed compared a "conventional" neighborhood (Al Salamat) to a "sustainable" neighborhood (Shaubat Al Wuttah) by applying a customized set of sustainable design principles, an approach that informed and expanded the discussion of SUFs in the Arabian Gulf (Ahmed, 2017). Extending Jabareen's matrix, his inquiry is particularly responsive to the cultural nuances of sustainable social housing in the region. He merges aspects such as density with compactness and added elements like privacy, safety, imageability, resilience, accessibility, local autonomy, and choice to his SUF matrix (Ahmed, 2017).

While Jabareen and Ahmed examined SUFs, other scholars approached sustainability in Arabian Gulf architecture and urbanism as a discourse on political, economic, and social policy. Yasser Elsheshtawy (2018) reviewed various examples of Arabian Gulf projects to demonstrate how the commitment to construct sustainable built environments is deeply intertwined with the process of nation-building. He argues that a "greenwashing" strategy underpinning the rhetoric of sustainability has been adopted by Gulf nations to appease foreign entities and gain international recognition (Elsheshtawy, 2018, p. 3). While the focus on sustainability fulfills the New Urban Agenda (NUA), he claims the practices remain neither sustainable nor resilient. Urban policies that support housing sprawl, residential segregation, privatization of public space, and higher land values demonstrate this trend. As a result, governments in the Arabian Gulf have tended to focus on achieving technologically enhanced environmental measures of sustainability rather than resolving social concerns within their communities. Meanwhile, the Arabian Gulf city remains car-centric, less energy-efficient, and characterized by low-density developments and a scarcity of freshwater resources (Elsheshtawy, 2018, pp. 4–7).

Similarly, Eric Verdeil asks: "Why does green urbanism in MENA countries seem to be underdeveloped?" (2019, p. 36). He observes that in the Arabian Gulf, support for urban and architectural sustainability is intertwined with achieving social stability and the strategy of *worlding*, wherein nations base decisions on the extent to which they contribute to the image they wish to portray to the world—particularly that of their developed status (Verdeil, 2019, pp. 35–36). Pursuing social stability through the engagement of modern forms of consumption that may not be environmentally friendly undermines the commitments made by adopting environmental policies aligned with international standards. Urbanization, Verdeil remarks, "remains car-centric and privileges individual sprawling housing for the nationals, both of which can only thrive thanks to massive energy and resources consumption and environmental losses" (2019, p. 38). He thus concludes that the governance of sustainable urbanism in Middle Eastern countries lacks an overall concern for ecology and calls for ordinary urban practices to be examined and accommodated by policymakers through design intentions and building codes that demonstrate their commitment to local sustainability measures. These include strategies such as subsidy cuts to water, electricity, and gas services offered by the government that encourage reduced usage by consumers (Verdeil, 2019, pp. 37-39). Likewise, in his study of the sustainable ambitions of Masdar City, UAE, and the consequences of its implementation, Laurence Crot agrees with both Elsheshtawy and Verdeil, suggesting that urban sustainability schemes in the

Arabian Gulf have been geared to satisfy a "social contract" between the governments and people as a form of appeasement at the expense of impacting real change (2013).

Considering the sustainability of Kuwait's urban development, Muhannad Albaqshi recognizes that the country's modern neighborhoods possess a "latent" sustainability that has not yet been realized. Although Albaqshi notes that "Sustainability is already present in the blueprint of Kuwait's urban fabric" (2010, p. 108), preference for urban sprawl and car dependency hinder the development of aspects such as walkability and multimodal transportation. Based on Doug Farr's definition of sustainable urbanism, Albaqshi outlines ten core principles for assessing Kuwaiti neighborhoods: (1) limited population, (2) limited physical area, (3) mixed-use zoning, (4) urban characteristics, (5) prime access to public spaces, (6) pedestrian-friendly streets, (7) efficient mass transit system, (8) high-performance infrastructure, (9) local character in urban design elements, and (10) sustainability policies addressed at all scales. While Kuwaiti neighborhoods tend to meet the criteria of limited density, area, mixed uses, public space, and characteristics of urban design, Albaqshi notes the need for more pedestrian-friendly streets, along with an improved mass transit system, elements of urban identification and local character, and an environmental agenda through which poor waste management and energy consumption are addressed. For example, he proposes the revision of local building codes to discourage residents from parking cars on sidewalks (Albaqshi, 2010, pp. 116–118).

The issue of sustainable urbanism has recently been addressed in work examining the political connotations of social housing in the Middle East (Kilinc and Gharipour, 2019, p. 2). The authors note how the general move towards neoliberal economic practices in the region—particularly in the Arabian Gulf area—has accompanied a decline in centralized participation by governments in providing social housing due to high construction, infrastructure, and maintenance costs. This has resulted in public-private partnerships for the design and construction of social housing, which limits the possibility of participatory design for housing recipients, among other issues. Inevitably, such a change impacts equitable access to housing as a *process* provided by Middle Eastern governments, but it also establishes social housing as a crucial *product* in need of sustainable development.

Within this discussion, it is worth noting that sustainable social housing is crucial to Kuwait's push to reach its UN-mandated SDG goals. Yet scholars describe social housing in Kuwait—like many other Arab Gulf countries—as a "tradeoff" and "battlefield" between the state and its citizens (Sadik, 1996; Al-Dekhayel, 2000). As Mae Al-Ansari (2016) puts it, "The state gains leverage through the distribution of wealth and the establishment of institutions that confirm its national independence. In return, citizens accept material satisfaction and adopt the Kuwaiti political regime" (p. 264). Similarly, in the recent past, Kuwaitis appeared to consider government housing as their preeminent right as citizens—even more so than the right to vote (Sapsted, 1980, p. 106). Historically, massive social housing construction campaigns have driven the modernization of Middle Eastern nations (Sadik, 1996, pp. 32–35). Thus, the State of Kuwait continues to carry these visions, values, and ideals for social housing as the 21st century unfolds and it navigates the expectations of its citizenry and the world at large. The challenging question then becomes how the government negotiates these dimensions—as both *process and product*—considering its support for the SDGs and its commitment to creating sustainable living environments.

1.2 Urban governance and social housing in Kuwait

Kuwait's social housing initiative began in the early 1950s as one among many of the services offered by the new, modern, welfare state that emerged from the former pearling and trade center of Kuwait Town. The government's "cradle to grave" policy used incoming oil revenues to provide citizens with access to education, healthcare, housing, and employment. From inception, the policy focused on the overall wellbeing of the population, and this concern was reflected in the subsequent design of Kuwait City and its suburbs in 1952 by British planners Minoprio, Spencely, and MacFarlane. Suburban neighborhoods were designed as self-sufficient communities modeled on the English Garden City, with detached single-family dwellings, schools, and mosques. Based on the Perry (1929) "Neighborhood Unit" concept, these districts also featured secondary commercial nodes distributed among neighborhood blocks offering services such as dry cleaning, tailoring, and small shops, as well as the main service core containing a supermarket, government offices, a clinic, and other large commercial services. The intention was to create a neighborhood fit for the modern Kuwaiti lifestyle (Ghareeb, 2020).

Since its establishment, Kuwait's social housing program has been characterized by gradual, piecemeal distribution within neighborhood units in the form of houses, land plots with construction loans, and apartment units. Around 1952, social housing in Kuwait was established via plots in newly planned neighborhoods. These were exchanged for "appraised" housing in the town center, which would be demolished to accommodate the new modern Kuwait City center (a process known as *Tathmeen*, or "appraisal"). The funds received from the appraisals enabled families to construct modern, detached, single-family villas. Two-story housing units were also constructed directly by the municipality in the mid-1950s for those with limited income, and the demand for housing began to rise. The Housing Welfare Law came into effect in 1967, and the government's "Land and Loan scheme" saw it continue to construct and allocate detached and semi-detached housing to citizens, as well as offering special financing options with 30-year, interest-free loans to help a new generation of citizens construct homes. The 1970s and 1980s saw the first social housing apartment units, as projects such as those located in Sawaber and Sabah Al-Salem were commissioned to accommodate the rising values and reduced availability of land. This period also saw the emergence of dissatisfaction among middle- and lower-income housing residents, whose responses to National Housing Authority surveys revealed they were modifying their units during their first year of residency (Al-Ansari, 2016, pp. 282–284).

After much criticism of the income-based disparities in its provision, the government standardized social housing in the early 1980s to offer 400 m^2 plots for all, with a specific built-up area and set of program components. In doing so, it dispensed with apartment units as viable social housing options. Different versions of the land and loan scheme have since been implemented, with a few recent exceptions such as the distribution of a small number of detached houses under exceptional circumstances in 2021. In early 2005, the focus of social housing in Kuwait turned to self-sufficient satellite towns (Ghareeb, 2020, p. 88), with the PAHW currently distributing plots in South Sabah Al-Ahmed City (20,380 units) and South Saad Al-Abdullah City (24,508 units). Three additional cities are being planned at Khiran (45,000 plots), Sabriya (52,000 plots), and Nawaf Al-Ahmed City (52,000 plots).

This summary of Kuwait's social housing history demonstrates, among other issues, the trial-and-error approach to housing provision adopted since the establishment of the country's welfare state. It also demonstrates how the state has striven to achieve different forms of sustainable living, whether through equitable access to plots, the construction of housing units, the provision of financial options in the form of long-term, interest-free loans to support housing construction, or by prioritizing the general welfare of its citizens. These goals are reiterated in the country's latest National Development Plan for 2025 (General Secretariat of the Supreme Council for Planning and Development, 2020, 2020, p. 185).

1.3 The PAHW's current energy initiatives and housing developments

According to its Deputy Director General for Planning and Design, the PAHW is committed to achieving the energy goals set forth by the late Emir Sheikh Sabah Al-Ahmed Al-Sabah, in line with the 4th Kuwait Master Plan 2040: Towards a Smart State. As such, the PAHW has set the following energy initiatives as targets for 2030, some of which have already been achieved:[1]

- 20% of the energy needs of new public buildings will be met by renewable sources.
- A smart sustainable model home will be designed and constructed.
- 1,184 social housing units that use renewable energy for water heating will be completed in the neighborhood of East Sabah Al-Ahmad.
- New zoning codes will be developed to ensure 10% of housing energy needs are covered by renewables.
- New building specifications that include renewable energy and green building regulations will be developed to ensure that 5% of new-build energy needs are met by renewables.
- A feasibility study will be conducted that explores the viability of district cooling through 40% use of renewable energy in new social housing neighborhoods.
- Smart cities will be designed and constructed.

1 PAHW, *Innovation for a Better Quality of Life in Cities and Communities: Accelerated Implementation of the New Urban Agenda towards achievement of the Sustainable Development Goals*, Presentation slides, 2018.

FIGURE 1
House 2035 in Jaber Al-Ahmed neighborhood.

1.4 Public buildings

The Head of the PAHW's Electrical and Renewable Energy Division claimed that the 20% target to use renewable energy in public buildings has been accomplished by using solar photovoltaic systems, water treatment systems, solar water heating, and wastewater management. Even higher percentages of renewable usage have been achieved in some public buildings such as mosques, schools, clinics, and police stations. As of 2018, over 80 public buildings had been completed, over 200 buildings were under construction, and approximately 453 buildings were in the tendering phase, all of which use at least 20% renewable energy.[1] Furthermore, the PAHW hopes that district cooling will be a standard feature of future neighborhood designs.

1.5 Smart sustainable model home (House 2035)

In 2012 and with the support of the private sector, the PAHW began the process of designing, constructing, furnishing, and maintaining House 2035, a smart sustainable model home that encapsulated the Public Authority's outlook on embracing sustainable living by encouraging Kuwaitis to adopt a more environmentally sensitive lifestyle (Figure 1). A low-energy prototype, House 2035 is a 400 m^2 detached, single-family villa located in the Jaber Al-Ahmed neighborhood that is fitted with sensor technology to display "normal" home consumption of resources (e.g., water and electricity) (National Technology Enterprises Company, n.d.). Eight smart meters are installed throughout the house to monitor the energy produced by solar panels, including electricity consumption, a significant portion of which comes from air conditioning. Inaugurated on 20 February 2020, House 2035 has produced real-time readings since at least October 2021 and is expected to supply the PAHW with data for 5 years. As a "showcase house," House 2035 integrates efficient systems such as PVC solar panels, variable refrigerant flow (VRF) air conditioning systems, solar water heating, and grey water treatment.

The bases for comparison include HVAC, lights, sockets, water heating, and other outlets for water and electricity consumption.

Named after the sustainability pledges made by the State of Kuwait to the UN, House 2035 provides a model of smart and sustainable building design, construction, furnishings, and maintenance. The villa was designed by architectural firm Dar SQC International Consultants with specific targets for technology and materials: availability, accessibility (physical or local access), and affordability. Market availability, distance to the supply chain, availability of labor, and the costs of transportation, installation and maintenance of technology, and building materials were all factors considered by the PAHW. The villa boasts features such as an EV charging station, LED lighting, energy auditing, and solar power, and is GSAS four-star certified (National Technology Enterprises Company, n.d.).

1.6 New zoning codes and building specifications

As for new zoning codes, in 2019 PAHW adopted an *Urban Design Manual* which incorporates sustainability measures linked to seven urban design principles (PAHW, 2019, p. 9). These include:

- a compact city form adapted to the Kuwaiti desert landscape,
- small-scale and mixed-use neighborhoods,
- a diverse and polycentric city,
- roads as connectors within a grid that is less hierarchical,
- integrated public transport within transit-oriented neighborhoods,
- pedestrian-friendly and green urban spaces,
- urban identity, character, and cultural sensitivity.

1.7 Smart cities

PAHW is also leading the country into the future through its endeavor to produce smart cities via social housing. In fact, the western neighborhood of South Saad Al-Abdullah has since 2016 been advertised as the region's first city to be designed with environmentally friendly and smart systems in mind (Al-Abdullah, 2017; Kuwait News Agency, 2016; Kuwait News Agency, 2019). The smart city model has been adopted from and in partnership with South Korea to bring this 6400-ha city for 400,000 residents to life (Euronews, 2018). With six main approaches that encompass smart living, smart environment, smart welfare, smart utility, smart mobility, and smart safety, features like waste management, air mist cooling systems, street light remote management, EV charging systems, and water grid management become tools to realize a more sustainable, efficiently managed built environment through the monitoring and regulation of energy consumption. To achieve this vision, various public services in social housing neighborhoods must be retrofitted and/or outfitted with new systems.

More recently, the XZero development was unveiled by Dubai-based URB as a car-free, smart, zero-carbon city for 100,000 residents in Kuwait (2022). The scheme of this 1600-ha city in Kuwait's southern region focuses on density and green spaces to enhance walkability supported by a green circular economy to provide residents with food and energy security (Florian, 2022). With features like 100% renewable energy and water recycling, zero-waste infrastructure, and a productive landscape, XZero has been described as "a unique resilient landscape which will promote health, wellbeing and biodiversity" (URB, 2022). Among other smart systems, Artificial Intelligence is employed to provide predictive analysis on consumption and production, and for aspects such as water management in efforts to create a city of resiliency and liveability (URB, 2022).

2 Materials and methods

This paper adopts an evidence-based methodology to investigate and evaluate how different dimensions of sustainable urban forms operate within the social housing building typologies of Kuwait. It aims to do so by systematically examining the *process-to-product* relationships entailed in realizing built form. This includes assessing how design elements and decisions facilitate experiences of movement (pedestrianism), social interaction, neighborhood belonging and identity, and choice in the process-to-product spectrum. Semi-structured interviews and field observations were adopted to collect necessary off- and on-site data. These data were analyzed using the matrix of design principles set out by Jabareen (2006) and Ahmed (2017). Due to similarities between Kuwait and the UAE in such aspects as physical proximity, climate, culture, history, religion, language, governance, and economy, Ahmed's matrix was considered an appropriate guide to the methodology and analysis used in this study. His criteria of privacy, safety, imageability, resilience, accessibility, local autonomy, and choice were viewed as highly relevant to evaluating the sociocultural context of SUFs in Jaber Al-Ahmed.

2.1 Site selection

The neighborhood of Jaber Al-Ahmed was selected after careful consideration of the PAHW's social housing projects. The following questions informed this decision: (1) whether all PAHW projects completed since the authority was established in the 1950s should be considered; (2) whether only neighborhoods with housing units constructed by the PAHW should be examined or only plots distributed for housing should be included; and (3) whether only one or a few of the numerous neighborhood projects would provide sufficient evidence to generate robust conclusions.

Upon investigation, the diverse approaches to design in each social housing neighborhood emerged as a necessary criterion. For example, the neighborhoods of South Sabah Al-Ahmed, AlMutlaa, and South Saad Al-Abdullah vary considerably in terms of their plot arrangements (Figure 2). The matter of scale also influenced our choice of which site to study, raising various issues including but not limited to connectivity, methods of transportation, and employment. This, along with the diversity of housing types and access to information on design process and evidence of occupancy guided the selection process.

The clearest example of a design approach to social housing was identified as the Jaber Al-Ahmed neighborhood designed in 2007 by Pan Arab Consultant Engineers (PACE). Although the project predates the UN Agenda signed by Kuwait in 2015, aspects of both Jabareen's and Ahmed's design principles seem to be embedded in its conceptual

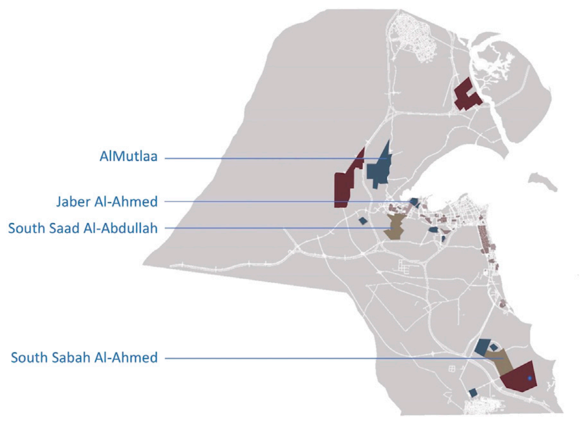

FIGURE 2
Map showing various PAHW social housing developments (source: by authors based on Public Authority for Housing Welfare, 2022).

foundations. In other words, it enabled an analysis of process-to-product to be carried out through the investigation. The neighborhood also features a diversity of housing types such as villas, apartments, and future townhouses, unlike neighborhoods such as Sabah Al-Ahmed. Additionally, and perhaps most importantly, the developmental status of Jaber Al-Ahmed provided evidence of residential habitation, appropriation, and community building whereas the relatively newer neighborhoods mentioned above were designed after 2015 and the processes of plot distribution and housing construction remain incomplete.

2.2 Semi-structured interviews

Semi-structured interviews were conducted with representatives of government authorities and design firms to shed light on the design and construction processes involved in Kuwait's sustainable social housing. Officials at the PAHW's Department of Planning and Design answered open-ended questions about the process of completing social housing projects in general and the design of the Jaber Al-Ahmed neighborhood in particular. Another PAHW official responsible for renewable energy provided insight into the sustainability initiatives of the institution. All interviewees were either architects or engineers familiar with the architectural design and construction process of social housing projects.

2.3 Site observations

Neighborhood residents' behavior was documented by collecting and analyzing aerial images and on-site photographs. Design principles were applied (1) to evaluate the success of the design of the neighborhood, street, plot, and housing unit in terms of achieving or promoting accessibility, mixed use, diversity, mobility, density, greening, and passive solar design, and (2) to document evidence of choice, local autonomy, privacy, and imageability. To determine the distances between services and housing plots, Google Earth measuring tools and features were employed. Local building codes for housing design, such as maximum built-up area, building height, and setbacks were used to contextualize and further assess the elements mentioned above.

2.4 Analysis of design principles

This evaluative analysis of the design principles of Kuwaiti SUFs draws on the criteria of Jabareen (2006) and Ahmed (2017) and is proposed by the authors of this study as a new sustainability approach to be adopted by the PAHW in its social housing schemes. Specific measurements and methods of examination were used to evaluate each criterion throughout the project stages of Planning, Design, Construction, and Occupancy (Table 1). They received a final assessment of Highly Considered, Partially Considered (as an aspect of either process or product), or Not Considered (Table 2). While a "Highly Considered" evaluation denotes that all dimensions described in the definition of each design aspect are satisfied, a design aspect is "Partially Considered" when at least one dimension within its definition is fulfilled, and an evaluation of "Not Considered" indicates that no defined dimensions have been addressed. A numerical scoring system has been adopted to support the analysis, as "0" refers to aspects "Not Considered," "1" refers to aspects "Partially Considered," and "2" signifies "Highly Considered" aspects. Tabulations of scores are provided for each design principle for reference.

3 Results

3.1 Current challenges for the PAHW

The path to implementing the PAHW's sustainability strategies—including the production of sustainable neighborhoods—has not been entirely smooth. Apparently, this is not due to administrative failings on the PAHW's part but results from a lack of cooperation, communication, and overlap amongst the different government administrations and their roles in the design and construction process. For example, the PAHW's Deputy General recounted the authority's attempts to implement multiple regulations and codes for social housing projects such as approving new zoning codes and building specifications, as well as the installation of various forms of renewable energy systems (e.g., PVC panels on the roofs of schools and public buildings like clinics and police stations). Unfortunately, long-term operations and maintenance procedures for the systems proved unsuccessful. Even aspects of social sustainability such as walkability and accessibility were impacted: the planning of recreational elements like parks and water features must observe Environmental Protection Authority (EPA) regulations and require approval from the Public Authority for Agriculture Affairs and Fish Resources (PAAAFR), which operates and maintains them after construction is completed. Needless to say, irrigation water shortage issues in neighborhoods like JA appear to have prevented the PAAAFR from accepting the project handover.

Moreover, the PAHW's Deputy General clarified that—even with new zoning codes—there was no guarantee that citizens would follow the renewable energy regulations unless these were upheld by

TABLE 1 Design principles matrix with definitions, based on the SUF principles of Jabareen (2006) and Ahmed (2017).

Design Principles	Adapted Definitions
Urban Density	The relationship between a given area and the number of people or dwelling units in that area (e.g., 50 dwelling units per hectare)
Urban Diversity	The availability and variety of services, uses, and housing options or types in the neighborhood
Accessibility	The availability of services within walking distance in the neighborhood
Mixed use	Access to and availability of various commercial services such as small shops and offices that serve the daily needs of residents. This includes multiple uses of space and work-home arrangements in the neighborhood.
Mobility, and sustainable transport	The availability of calm streets, shaded and well-lit pathways, safe bike routes with parking stands, and interconnected street networks in the neighborhood.
Passive solar design	The application of multifarious design methods for the purpose of energy efficiency and reducing energy demand and consumption in the area.
Greening and environmental quality	The availability of green spaces, open public spaces, and private green spaces in housing units that improve the quality of living in a neighborhood.
Choice	A resident's ability to select different modes of transport, housing, and services in the neighborhood.
Safety and security	The availability of a safe environment, visual surveillance in the public realm, and inclusive design for children, the elderly and disabled (e.g., playgrounds, street crossings, speed limits, ramps for wheelchair and stroller access, handrails, braille typeface, etc.).
Privacy	The availability of private and semi-private outdoor spaces in the neighborhood.
Imageability	The availability of features or elements that distinguish a neighborhood's character and identity and remind people of their location. It includes landmarks (buildings, popular businesses, public art, gardens), colors, shapes, and materials that create mental images for residents and visitors.
Local autonomy	The ability of residents to impact their built environment by affecting change in community regulation, policy, and decision-making. This includes residents' involvement in designing their neighborhood.

Kuwait's Municipality via the administration of new laws and the mobilization of divisions to penalize transgressions. The Deputy General emphasized that the approach needed to be holistic rather than piecemeal. As a result, he projected that a restructuring of government authorities would be required to achieve the renewable energy requirements. Hence, in Kuwait, the goal of achieving 15% or 20% reliance on renewable energy through minor interventions in building design and construction is much easier to accomplish than operating and maintaining the systems themselves.

The Head of the Electrical and Renewable Energy Division at the PAHW agreed that regulatory setbacks challenged its efforts to achieve more sustainable social housing. For example, electricity codes and regulations needed updating—a process that requires various government entities to collaborate with the Ministry of Electricity & Water & Renewable Energy (MEW). In addition, she highlighted technological challenges with some products, such as PVC panels that are especially sensitive to Kuwait's climate. She explained that maintenance was difficult due to the dusty and humid Kuwaiti summer, and performance was often impacted because of dirt accumulation on the panels. Water is needed to remove the accumulated residue and is difficult to obtain in isolated desert sites. As a result, water tankers have periodically driven to sites where water is scarce and sprayed the panels—a solution that is costly, inefficient, and unsustainable in terms of water usage and resource management. On the other hand, dry cleaning processes increase the risk of permanently scratching and damaging the panels.

3.2 The design process

3.2.1 Commissioning a PAHW project

The PAHW has the capacity for large-scale project design. The process of commissioning a social housing project first requires the authority to request a land allocation from Kuwait Municipality, which, referring to the master plan, must select a site appropriate to the proposed function (Figure 3). Following approval, the municipality hands over the site to the PAHW, which checks for any obstacles or irregularities and proceeds to plan the site. This stage requires a committee comprised of ministry representatives to approve the project since it involves multiple public services, such as mosques, schools, supermarkets, police stations, clinics, post offices, commercial shops, and other facilities, including green spaces. Once this consortium of ministries and public authorities approves the project, the Council of Ministers is informed for reference.

The PAHW then drafts and announces a request for proposals (RFP) in the media (local newspapers and its website) wherein a terms of reference (ToR) document is issued to guide the submission of proposals by design consultants. This includes the project goals, activities, scope of work, and tasks to be performed. It covers how the site is to be organized in terms of appropriate allocation and zoning of public services, infrastructure planning, residential zoning, and road design and construction. Various studies are required by the ToR, including traffic studies, site surveys, soil testing, and studies of topography, demographics, and environmental impact. Design firms respond by submitting project proposals. Once the winning

TABLE 2 Assessment of Sustainable Urban Form Considerations at Jaber Al-Ahmed neighborhood, Kuwait.

Design Principles	Project Stages				Level of Consideration at JA
	a. Planning	b. Design	c. Construction	d. Occupancy	
Urban Density	*2*	*2*	*2*	*2*	**8**
	*Specified in TOR**	*Observed in design*	*Observed in construction*	*Maintained by residents*	**Highly Considered**
Urban Diversity	*2*	*2*	*0*	*0*	**4**
	Limited to two social housing types	*Limited to two housing types; Isolated services and housing types*	*Isolated services and housing types*	*Isolated services and housing types*	**Partially Considered (as process)**
Accessibility	*0*	*2*	*0*	*0*	**2**
	Not considered in TOR	*Observed in design*	*Not constructed for walking*	*Not walkable*	**Partially Considered (as process)**
Mobility, and sustainable transport	*2*	*2*	*0*	*0*	**4**
	pedestrian pathways, mass transport and street networks considered in TOR	*Shaded pathways, calm streets, bike routes and street networks proposed in design*	*No shaded or safe pathways or bike routes constructed*	*No shaded pathways or safe bike routes*	**Partially Considered (as process)**
Mixed Use	*1*	*1*	*1*	*1*	**4**
	Commercial services considered in TOR; no work-home arrangement	*Commercial services designed; no work-home arrangement*	*Commercial services constructed; no work-home arrangement*	*Commercial services operate; no work-home arrangement*	**Partially Considered**
Choice	*0*	*0*	*0*	*2*	2
	Not considered in TOR	*Not considered in design*	*Not considered in construction*	*Choice of housing plot*	**Partially Considered (as product)**
Greening and Environmental Quality	*0*	*2*	*0*	*0*	**2**
	Not considered in TOR	*Incorporated as design concept*	*Open spaces completed; No landscaping*	*Residents convert open spaces to parking, storage, fenced lots*	**Partially Considered (as process)**
Safety and Security	*1*	*2*	*1*	*1*	**5**
	Design for disabled considered in TOR	*Considered in design concept*	*Limited to safety; no inclusive design*	*Limited to safety; no inclusive design*	**Partially Considered**
Privacy	*0*	*2*	*2*	*2*	**6**
	Not considered in TOR	*Fereej design concept*	*Considered in construction*	*Observed by residents*	**Partially Considered**
Imageability	*0*	*0*	*0*	*0*	**0**
	Not considered in TOR	*Not considered*	*Not considered*	*Not considered*	**Not Considered**
Passive Solar Design	*0*	*0*	*0*	*0*	**0**
	Not considered in TOR	*Not considered*	*Not considered*	*Not considered*	**Not Considered**
Local Autonomy	*0*	*0*	*0*	*2*	**2**
	Not considered in TOR	*Not considered*	*Not considered*	*Considered in plot selection and greening*	**Partially Considered (as product)**

Numerical indicators:
(0) – Not Considered
(1) – Partially Considered
(2) – Highly Considered
*Text in italics notes why each design principle was assigned its numerical indicator(s).

proposal is announced, the design is developed in consultation with the PAHW.

The bidding and tender process follows, and the winning contractor is tasked with drawing up the construction documents, which are effectively guidelines for translating the concept into the constructed reality. Because contractors often assign shop drawings to sub-contracted design firms, the original project concept typically undergoes multiple iterations before arriving at its final form. Once the project is completed, it is handed back to the PAHW, which is also involved in supervising building works through its construction

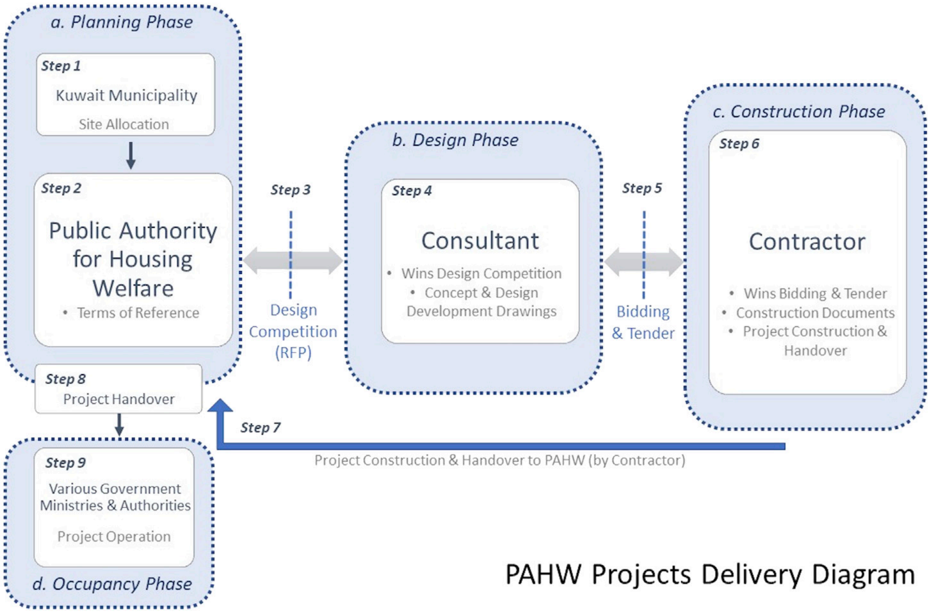

FIGURE 3
The PAHW project delivery process, based on semi-structured interviews with PAHW officials.

department. The PAHW then transfers the public buildings to their respective ministry authorities for operation and maintenance and distributes housing plots to the citizenry.

The PAHW officials stated that these process-to-product procedures were sometimes delayed due to the apparent lack of cooperation from the ministries involved. They claimed that some ministries do not accept the project handover and refuse to allocate budgets for operating and maintaining the buildings. The latter may feel that if they have not been involved in a project's design and construction beyond the initial planning stage, they should not be tasked with subsequently operating and maintaining it. Accordingly, some Ministries have refused to accept project delivery from the PAHW, whose Deputy General Director attributed the lack of cooperation to the following: (1) the officials' lack of awareness of the nature and importance of implementing sustainability strategies; (2) the absence of guidance or clear directives from policymakers about the importance of applying sustainability measures to projects; (3) the lack of clear government budgetary allocations to sustainable strategies and systems; and (4) the lack of incentives for implementing sustainable design across the state sector.[2] These issues were seen most prominently in the reduction of JA's "Green Finger" concept to isolated green spaces on paper, which have taken the form of barren, fenced desert islands within the neighborhood blocks.

2 Until Kuwait signed the UN's 2030 Agenda in 2015, there has been no clear roadmap to sustainable development, even though one should acknowledge the "latent" aspects of Kuwaiti neighborhoods in this respect.

3.2.2 The move towards privatization of public services

In recent years, the PAHW has shifted its vision towards privatizing its public services. Its processes seek to design successful neighborhoods that account for the needs of residents and the wider market. This trend reflects the Middle East's wide embrace of neoliberal economic policies and the observably shrinking role of central authorities in housing provision (Kilinc and Gharipour, 2019). In Kuwait in particular, this shift has been encapsulated by the introduction of public-private partnerships, or PPPs, into the PAHW's projects. In these models, the PAHW commissions an organization to develop the project, which is then subcontracted to a design consultant and construction firm for completion (Figure 4). The PPP model aims to both reduce delays in design and construction and short-circuit any mediations that might interfere with the progress of the project. The involvement of the private sector accelerates the design and construction schedule while allowing the developers to benefit from an allotted time frame before transferring the project back to the PAHW, which in turn profits through continued operation and maintenance of the project after the handover is complete.

The J3, J4, and J5 zones at Jaber Al-Ahmed are being developed on the PPP model between the PAHW and the private sector (Figure 5). In August 2020, a PPP contract was awarded to local companies including Mabanee (a large real-estate development company) to design, construct, finance, operate, maintain, and transfer the investment to the PAHW (SaudiGulf Projects, 2020; Public Authority for Housing Welfare, 2022). J3 is currently being designed as a commercial zone with 276 housing units attached (Makhoul, 2021). In detail, it consists of two large-scale shopping malls, open green spaces, mosques, and residential building types (townhouses and apartments with parking spaces) developed as a

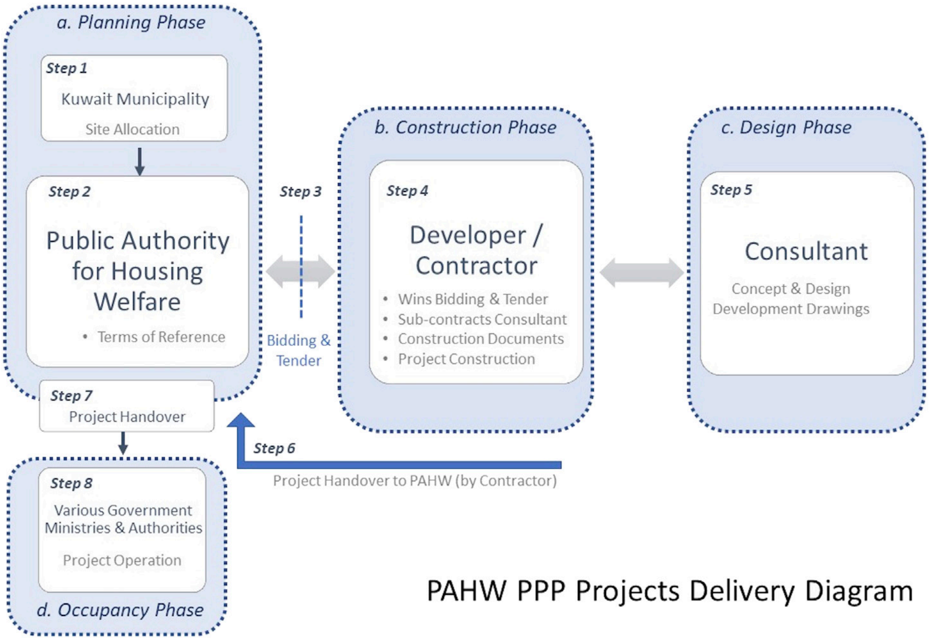

FIGURE 4
The PAHW project delivery process (PPP approach), based on semi-structured interviews with PAHW officials.

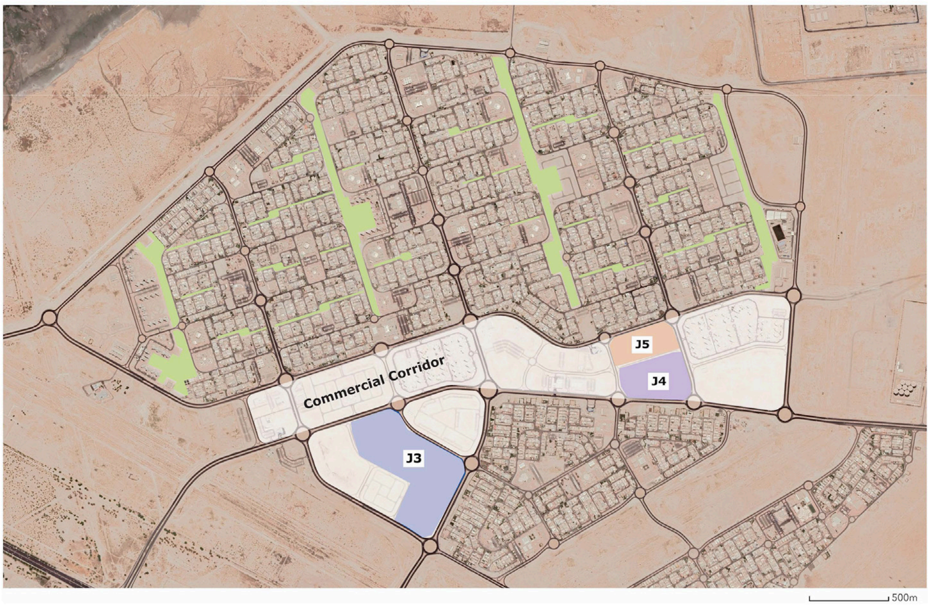

FIGURE 5
Map of Jaber Al-Ahmed neighborhood showing neighborhood blocks, green finger strips, the commercial corridor, and PPP investment zones J3, J4, and J5. (source: edited by authors based on Google. (n.d.), 2022).

PPP investment opportunity between PAHW, Mabanee, the contractor, and the design consultant. The benefits of this neighborhood design include its walkability, its community gathering spaces, and the easy access it provides to commercial activities at the malls.

3.2.3 The PAHW's design components for Jaber Al-Ahmed

The PAHW's initial aim for Jaber Al-Ahmed was to develop a "contemporary city to support Kuwait's growing population," that would offer a self-sufficient and "unique and progressive style of living" (PACE Architecture Engineering + Planning, n.d.). The design of the neighborhood, located roughly 22 km west of Kuwait City and slated to house a population of 80,000, was to include a mix of low- and high-density housing types, low-rise apartment buildings, shopping malls, government and municipal buildings, sports facilities, private universities, and hospitals on 1,244.54 ha (Figure 5). At the smaller residential scale, and in line with local neighborhood design schemes developed since the 1950s, mosques, shops, schools, and parks had to be situated within walking distance from people's homes. At JA, villas must follow Kuwait Municipality building codes that restrict 400 m^2 plots for detached single-family housing to a maximum three-floor height of 15 m, a maximum built-up area of 210% (with 120 m^2 permitted on the top floor) with setbacks of 2 m from the service road and 1.5 m on all other sides of the plot (Kuwait Municipality, 2022). The project's RFP encouraged bidders to use urban design thinking creatively and propose environmental solutions.

3.2.4 The Terms of Reference (ToR)

The Terms of Reference (ToR) for the Jaber Al-Ahmed neighborhood project were issued in December 2005 with the project vision to be developed by mid-2007, a duration of 546 days or about 18 months. The ToR describes the project's main components: the neighborhood would offer about 4,921 plots or houses for a population of 80,000 people. Moreover, it would provide a commercial zone for private sector engagement in the form of shopping malls, private hospitals, universities, and schools, an Olympic village, and high-rise investment housing of a relatively high density at 100–150 m^2 per apartment. Housing types would be offered in low-density, single-family "villa" plots of 400 m^2 as well as what the PAHW termed "vertical housing" in the form of six-story apartment complexes on 1,000 m^2 plots containing 400 m^2 apartments. Services to promote a self-sufficient neighborhood would include health clinics, schools, supermarkets, safety facilities, artisan spaces, and leisure and entertainment spots.

The government assumed this solution would help to provide Kuwaiti citizens with equal, or at least equitable, access to housing. They attempted to further incentivize apartment living in the ToR by explicitly encouraging consultants to consider how they would market this type of housing to Kuwaitis. Consultants were also encouraged to align new methods of neighborhood planning and housing design with the Third Kuwait Master Plan and with conditions in neighboring urban areas as well as the PAHW's recommended land use plan. They were additionally urged to incorporate non-conventional methods of wastewater treatment and recycling. These instructions required the consultant to conduct environmental studies and opened the door to SUF design thinking. The ToR also aimed to foster a cooperative ethos among government entities to develop the overlapping services of facilities operated and maintained by the Ministries of Health, Interior, Education, Awqaf & Islamic Affairs, the Public Authority for Youth & Sport, and the PAAAFR.

However, the instructions were essentially limited to those described above. For example, while the consultants were specifically required to submit traffic studies using different platforms and methodologies, features specifically designed for pedestrians and people with special needs were barely mentioned beyond the advice to consider these profiles when planning the site (e.g., by allocating pathways and pedestrian bridges). Similarly, there was little consideration for human experience, identification in space, and movement in terms of design instructions, studies, and deliverable proposals. Interested parties were expected to submit sufficient studies of demographics and social context, but no explanation of how to do so was provided. The ToR can thus be viewed as car-centric, with the prospective designs requiring minimal study of alternative/mass transportation solutions.

While the ToR covered general information about the social and demographic profiles of the project's residents, economic and feasibility studies for investment opportunities at JA were articulated in greater detail. For example, the PAHW issued explicit instructions to maximize profits from the commercial zone, while there was a missed opportunity to amplify artisan spaces as empowering the entrepreneurial potentials of citizens of all ages and genders. These spaces could have been explicitly framed as spaces of production (i.e., to support citizens' earning capacity) as opposed to spaces of consumption (i.e., to encourage citizens' spending).

3.2.5 The design competition

The JA neighborhood's design resulted from an open design competition established and publicized by the PAHW, with the winning proposal submitted by PACE. The project design was developed by PACE in collaboration with the PAHW but was tendered by the authority, which assigned a contractor to complete the shop drawings and construct the project. The original concept ultimately underwent three to four iterations and translations—from designer to client and contractor to sub-contractor—before reaching its final form.

While sustainability was not a clearly articulated initiative in the PAHW's ToR for the design of the JA neighborhood, the PACE executives explained that this practice was common in the government sector, where design consultants are encouraged to submit innovative project proposals. Consultants can also suggest modifications or additions to zoning codes, building regulations, and specifications for Kuwait Municipality and the PAHW to consider. These points are consistent with the proposed coastal park that features in the concept diagrams of the north of JA.

To address the type and scale of public services proposed for JA, PACE contacted all the government authorities to gather their programmatic requirements. Once the information was received, the program was compiled. The design of the project's commercial services zone (or corridor) resulted from PACE's efforts to communicate with the authorities (Figure 5). Thus, the positioning of elements such as the Olympic village and educational zone (to the east and west of the site, respectively) ensured minimum disruption to the neighborhood in terms of traffic, noise pollution, and overall safety.

3.3 Product: Sustainable Urban Form at JA

Unfortunately, when comparing PACE's design proposal for JA to the completed neighborhood, the project's feature Green Finger concept is difficult to distinguish. Barren islands and open desert spaces have been taken over by awnings for private parking spaces and fenced in by trees—an apparent encroachment by neighborhood residents. This result cannot be attributed solely to the PAHW, PACE, or the contractor. From the conception of the design by the consultant until the design documents move to the contractor for tender and bidding, the project undergoes multiple iterations before its final form takes shape. Yet again, one must acknowledge the tension in designing and delivering government projects, wherein the vision is not always fully realized by the contractor, who completes shop drawings according to a foreign architectural concept and builds the project at competitive costs. In the current case, this all-too-common outcome of urban and architectural projects eroded the infrastructural nuances of sustainable living in the social housing project.

JA residents have already called on the government to provide essential services like access to mass transportation (e.g., opening bus routes), beautification of the neighborhood, and the opening of various schools (Arab Times, 2019a). Such provision may be considered less a design issue than one of management, operation, and maintenance. However, the process and product of design inevitably inform the long-term success and longevity of social housing projects like this. More importantly, one wonders how well the recent shifts in decision-making address aspects of sustainable living, and whether these new measures of social housing production will attract Kuwaitis to live in the neighborhoods.

3.3.1 Density

Given the neighborhood was designed for a population of 80,000 on 1,244.54 ha (PAHW, n.d.), JA's per hectare population density (pph) only narrowly exceeds the target parameters established by Ahmed (2017) (50–60 pph) at 64.3 pph. While residential density in the design process was primarily calculated using the information provided by the PAHW and PACE as a general guide to both commercial and residential units, its calculation in the design product extracted values directly from the neighborhood design (i.e., where different site densities could be isolated) (Pont and Haupt, 2009). This yielded two ways of calculating density, which the researchers attempted to reconcile by understanding the relationship between JA's commercial and residential density (Figure 6). While the ToR guided the designer and predetermined overall density during the design process, it only determined the projected population of 80,000 people, without specifying the number of site users such as residents, visitors, and commercial and government employees. Accordingly, the residential share of the neighborhood was calculated to be about 25% of the total based on a selected area of interest. Hence, it is inferred that JA had achieved the appropriate residential density and is Highly Considered as a criterion for the design of SUFs.

3.3.2 Diversity

JA offers detached and vertical social housing options. However, their design undermines the SUF criteria in two ways: (1) it lacks diverse plot sizes since all plots for detached housing are 400 m^2 to ensure equitable distribution and (2) these different housing options are physically separated from one another. In other words, each housing type is zoned and relatively isolated from the others. One case in point is the arrangement and location of vertical housing (six-story apartment complexes) throughout JA (Figures 5, 7). While these have been dispersed throughout the neighborhood at different locations relative to commercial nodes, their proximity starkly resembles and recreates the conditions found at the apartment complexes of the Sabah Al-Salem Housing Project (SSHP). SSHP has desert islands that form a moat-like buffer zone around the housing project. Over time, this has enhanced the feeling of physical isolation and social stigmatization among its female residents (Al-Ansari, 2019). The sole difference is that JA's apartment units have been added in smaller groupings throughout the neighborhood such that on the master plan they appear less zoned and more "integrated" into their community environment. Yet from the pedestrian's perspective, the housing types are clearly separated in a way almost identical to Sabah Al-Salem, which has a strictly zoned master plan.[3] Thus the assessment of urban diversity at JA is Partially Considered as part of the design process and not fully realized in the design product.

In terms of social diversity, the JA neighborhood design provides Kuwaiti families with equal plots and imposes no income-based restrictions. Plots are distributed to families according to the date of parental marriage. It is therefore assumed that the families moving into JA are of a similar age: adult parents would belong to the same generation, while the ages of their children would also be more closely matched as a result.[4]

JA is also designed to offer diverse services in the form of large-scale hospitals, private universities, shopping malls, and sporting venues in the commercial corridor with smaller-scale clinics, schools, government offices, and supermarkets available in the main commercial zone. Small commercial shops, such as tailors, dry-cleaners, cafés, and salons are located closer to the plots in small and intermediate commercial zones. This arrangement is based on scale and is not a dynamic that might resemble mixed-use zoning where people live above their workplace or commercial service premises.

3.3.3 Accessibility

Accessibility, i.e., the ease with which a resident can reach services, is a challenge at JA. Ahmed (2017) states that services should be located 400–600 m from houses to allow ease of pedestrian access. At JA, the plots closest to the commercial nodes have the most convenient access to their services, while more distant alternatives can be over 900 m away (Figure 8). Given the absence of shading and well-lit pathways, such distances discourage pedestrianism and lower walkability, mobility, and choice.

Ahmed also advocates giving public transport such as bus systems priority use of the road and restricted lanes, with bus stops at intervals of 200–300 m linking housing blocks. The reality is unfortunately that the Kuwait Public Transport Company (KPTC) is neither granted road priority, nor restricted lanes for its buses. This is as true of JA as other neighborhoods served by the state (Rhode et al., 2017). While there are bus stop signs and special drop-off zones on main thoroughfares (such as ring

3 For details, see: Al-Ansari, M. (2016) "Masked in the Protective Act: Women, Public Housing and the Construction of Modern-National Identities in Kuwait." PhD. Dissertation, University of Cincinnati.

4 Kuwaiti families are defined as family units headed by a Kuwaiti male, regardless of the number of wives or their citizenship.

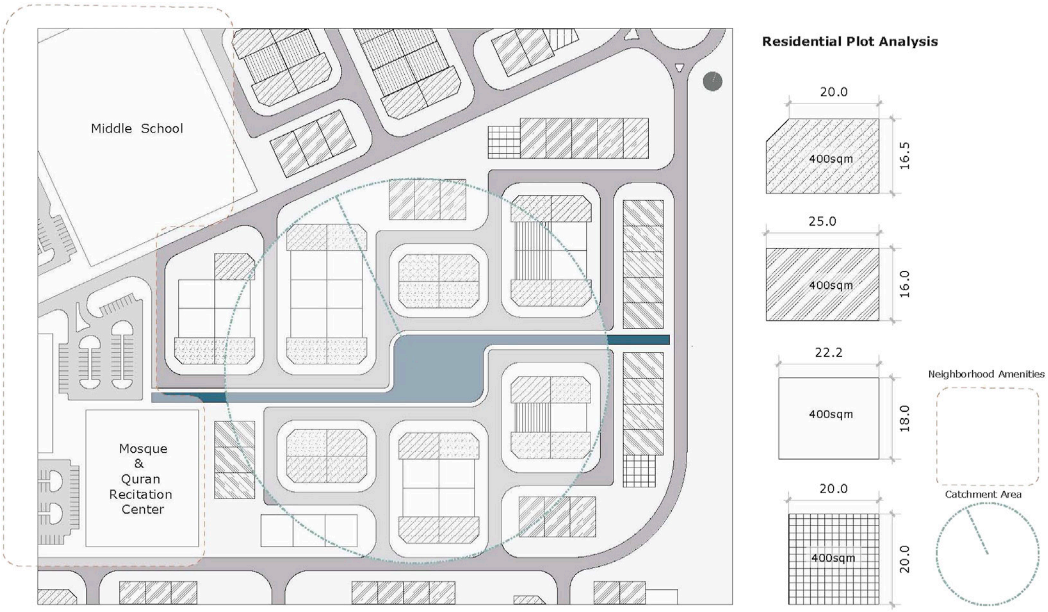

FIGURE 6
Plan diagram showing the nature of the cul-de-sac *fereej* configuration that promotes a sense of safety and security in the neighborhood, the plot setbacks from the street, street widths, and the catchment area from the main green finger strip to the neighboring dwelling units to assess access.

FIGURE 7
Image showing the displacement of JA apartment complexes relative to the low-density scale of nearby villas.

roads) across the country and in downtown Kuwait City, not many were observed in JA in late 2022 when the present study was conducted. This state of affairs has persisted even though, in January 2019, JA's housing association voiced its concern at the lack of public transport services in the area and by June 2019, the local cooperative society requested that KPTC begin providing its services to JA, mainly to serve commuting workers at the cooperative supermarkets (Arab Times, 2019b). Thus, accessibility is only Partially Considered at JA in design process and is yet to be addressed in the design product.

3.3.4 Mobility and sustainable transport

Identified by Ahmed (2017) as the availability of more than one mode of transport, mobility presumes the existence of interconnected street networks and residential blocks, the availability of shaded, well-lit streets, pedestrian and bicycle routes with parking stands, as well as calm streets and safe modes of transport. While JA's residential blocks are interconnected with street networks in the *fereej* concept, the in-between areas designated as green spaces have been left barren and abandoned. This discourages mobility, as the routes are dusty, hot, and dark at night, unwelcoming, and dangerous to pedestrians and cyclists. Moreover, the planned neighborhood does not include generous setbacks from sidewalks and walkways to benefit pedestrian residents (Figures 6, 9). In fact, plot setbacks are often taken over by parked cars, deterring residents from leaving their houses to walk to the nearest commercial service because there is no available space to walk. Children who ride their bikes are forced to do so on the neighborhood's roads; while these are seldom busy in the interior blocks, they remain a safety risk to those sharing the road with cars. Thus, mobility at JA is very limited, or Partially Considered, although the planning and original design stages may have proposed it.

3.3.5 Mixed use

This criterion addresses the variety of zoning opportunities in a particular area. A multi-use building offering commercial services and housing can limit commutes between home and work. It also encourages mobility, as commercial services are located closer to residential units. Ahmed specifies that 40%–60% of the floor area of mixed-use buildings should be dedicated to commercial, civic, and recreational purposes, while 30%–50% should be allocated for residential uses, and 10% should be used for public services (2017, p. 8). These proportions of mixed-use facilities were not available in JA's original design yet seem to be targeted by the J3 zone development, which includes a block of townhouses overlooking a central square near the anchor shopping mall.

FIGURE 8
Aerial image of JA showing the analysis of the neighborhood's Green Finger network and the walking distance (approximately 924 m) between a residential and service location. (base map source: Google. (n.d.), 2022).

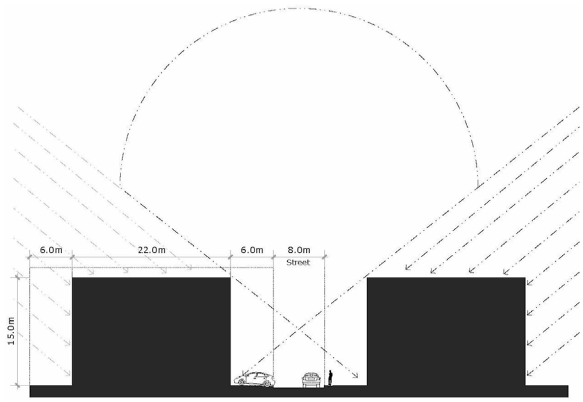

FIGURE 9
Sectional diagram demonstrating the plot setbacks from the street, the sidewalk and street widths, the indications of solar angles, and the exposure of street canyon facets to illustrate safety, security, privacy, accessibility, and the limited practices of passive solar design.

On the other hand, Albaqshi's study of Kuwait's "latent" urban sustainability asserts that the combination of residential types and commercial nodes—as well as their proximity to one another—in ideal Kuwaiti neighborhoods constitutes a type of mixed-use zoning (2010). If this definition is applied, then both the variety of the commercial services at JA and residents' access to these might attain

FIGURE 10
Image showing encroachment on JA's Green Finger strips by private gardens and covered parking spaces.

FIGURE 11
Image of one of JA's Green Finger strips: a barren open space has been enclosed to prevent residents from encroaching on the plot.

the mixed-use design criteria of SUFs. Hence mixed uses at JA are only Partially Considered.

Through the years, citizens have often expressed a sense of entitlement to social housing, which many view as a form of investment. At JA, this would explain why houses have been leased out to nursery schools and other for-profit organizations, signaling to government officials that the applicants did not actually require social housing as their primary source of shelter. By allowing such informal commercial activities to take place in neighborhood blocks, the government fosters an appreciation for mixed uses of land. It is nevertheless important to ensure that such activities are sustainable and to maintain order in the built environment.

3.3.6 Choice and local autonomy

Inevitably, accessibility is tied to convenience and choice in sustainable neighborhoods. Choice entails mobility, a variety of housing types, catchment areas that overlap neighborhoods, and the existence of a hierarchy of services at different scales. While mobility and housing variety are relatively limited at JA, a hierarchy of services at different scales has been adopted from the ideal Kuwaiti neighborhood model. For example, the master plan contains small, intermediate, and main levels of commercial nodes. The first level combines religious and commercial zoning: a local mosque and small grocery store, dry cleaning service, tailor, and/or food service. This enables residents to meet their everyday needs without having to visit the main commercial zone. The intermediate node comprises a religious zone such as a Quran recitation center, a commercial zone that includes cafés and salons, and a school zone. Finally, the main commercial core or node includes the full gamut of religious, commercial, academic, and public services. Public services such as the health clinic, post office, mosque, police station, and MEW offices are found near the main supermarket, restaurants, and commercial shops.

The evaluation of choice and local autonomy in JA's social housing provision can include the ability of each Kuwaiti family to select their plot. The PAHW randomly allocates plots to Kuwaitis via lottery-style draws. The authority's guidelines clearly delineate the name of the neighborhood and define which parcels of land are being distributed. In response to this somewhat disempowering way of distributing land, citizens encourage PAHW employees to put citizens who may want to swap plots in touch with each another. Another unofficial practice entails allocating plots to citizens of particular tribal and ethnic backgrounds by alerting members of particular social groups when many of their applicant members would be placed in the draw. Applicants may choose when to enter these draws and when to sit them out. This forms neighborhood enclaves according to tribal and ethnic affiliations that resemble the original organic formation of family-based residential clusters in Kuwait Town.

On the other hand, the individual's ability to autonomously impact and even alter regulations linked to Kuwaiti social housing is limited—especially because the service must satisfy the entire population. The Kuwait Municipality and PAHW are encouraged to collaborate to learn more about the unplanned, illegitimate suburban practices of neighborhood residents, so regulations may be adjusted to accommodate these needs where possible. For example, the practices of taking over public land in residential blocks to install parking awnings and enclose private outdoor space for personal uses such as gatherings and small-scale farming should be addressed by government entities. Such issues are indicative of a design problem while also providing an opportunity to generate ideas on legitimizing them in ways that do not interfere with public spaces (Figure 10). Thereby, zoning and building regulations could reconcile the legal tensions and safety risks involved in illegitimate practices while simultaneously acknowledging the validity of residents' needs; the Kuwait Municipality has already begun to address this issue (AlEnizi, 2020). Hence choice and local autonomy at JA are only Partially Considered in the design product.

3.3.7 Greening and environmental quality

This criterion covers the design of green spaces, public open spaces and streets, and private and semi-private spaces in residential neighborhoods. PACE's main vision for the JA master plan was its "Green Finger" concept that emphasized sustainable living (Figure 8). The name referred to linear strips of green open spaces interwoven into the fabric of the neighborhood and

FIGURE 12
An aerial image of the Green Finger strip at JA provides evidence of barren open space with scattered, fenced-off encroachments and private landscaping (source: Google. (n.d.), 2023).

leading north to proposed coastal parks overlooking Kuwait Bay. Programming for these green strips includes walkways, bike paths, tennis courts, and other sporting facilities that would create a recreational zone for weekend activities. The concept places the notion of greening and landscape design at the core of a successful neighborhood, implying that environmental quality is an integral part of the site infrastructure and must be designed and constructed accordingly. In other words, by the time the plots are distributed to citizens, the Green Fingers are presumed to have already been planted and furnished.

The project designer highlighted that the original Green Finger concept had shifted drastically between its inception and the finished product (Figures 11, 12). The original vision included more connected green walkways but appears to have been diluted to provide as many housing plots as possible, resulting in fragmented strips that have, in many cases, been appropriated for the purposes described above. Today the site's "green fingers" are islands whose barrenness points to a lack of planting, which itself exposes the dire need for cooperation and involvement from all authorities at the earliest stages of the design process. The "green fingers" have now been taken over by residents for private parking, private outdoor spaces, and small-scale farming. Hence, greening and environmental quality has only been Partially Considered as part of the design process.

3.3.8 Safety and security

Safety and security include measures of the density of a neighborhood and its compactness, the presence of mixed uses, and inclusive design for children, the disabled, and the elderly. Jane Jacobs (1961) and Newman (1973) argued that safety and security are achieved through visual surveillance in the public realm. Jacobs's "eyes on the street" approach encouraged members of the community to share in the responsibility of keeping neighborhood streets safe through visual surveillance. The notion positively impacts the design of neighborhood buildings, with architecture facilitating surveillance and ensuring there are no "blind spots" impeding parents' sight of their children playing on the street, or a street vendor's view of his or her goods, for instance (Jacobs, 1961).[5]

Upon examining JA's residential blocks, the "eyes on the street" theme is materialized in the proximity of the built-up housing plots (Figures 6, 9). In addition, the narrow street width reduces vehicle speed, especially since visibility is limited by cars parked on the sidewalks. However, the residential blocks rarely feature passersby—or "visitors" as Jacobs might call them—to provide diversity in terms of age, income, and working hours, as well as constant motion within the neighborhood. Between the morning and afternoon rush hours, like all suburban Kuwaiti neighborhoods, JA is relatively quiet as working parents and schoolchildren are away from home. Live-in staff comprising housekeepers, chauffeurs, and chefs remain but are not expected to participate in neighborhood protection practices. Housing plots near or adjacent to the small, intermediate, and main commercial nodes receive the added benefit of neighborhood surveillance throughout the day and additional parking spaces after working hours at the cost of greater exposure to rush-hour traffic and noise pollution.

Finally, the JA residential block design did not obviously accommodate the needs of children, elderly people, or those with disabilities. In general, such needs are normally handled on the premises according to the occupants of each plot. The commercial nodes, however, feature ramps for sidewalks and supermarket entrances to assist the movement of shopping carts, and reserved parking spots are provided for the disabled and elderly. It must be acknowledged that Kuwaiti suburban neighborhoods have relatively low crime rates, and this is in part due to the design of the self-sufficient garden city model, which discourages entry to traffic from outside the neighborhood. Consequently, security and safety do not seem to be a major focus for the designer at JA, as PACE adopted the already "latently" sustainable neighborhood design of the ideal Kuwaiti suburb. As such, safety and security are Partially Considered at JA.

3.3.9 Privacy

Privacy can be evaluated at the different scales of neighborhood, block, and building. It encompasses the design and orientation of

5 Jacobs promoted mixed uses, small blocks, and the activation of pavements to ensure neighborhood safety.

buildings on their plots to allow private transition spaces between interior and exterior, as well as the arrangement of housing plots in clusters or blocks.

At the neighborhood scale, privacy in JA incorporates the *fereej* concept, the traditional Kuwaiti neighborhood assemblage of housing units that ensures private living and calm streets (Figures 6, 9). The *fereej* is supported by *urf* (the customs of the Islamic Sunnah), which prioritizes neighborly relations and observes privacy requirements at the scale of the building, such as the prohibition of windows that overlook neighboring plots, and the inclusion of bent entry foyers that block visual access into the family or women's courtyard. Traditional Kuwaiti architecture prohibited exterior window openings in all rooms except for the men's diwan, which would most often overlook the public street or coastline: the windows of other rooms would face the interior courtyard (Lewcock, 1978).

This approach to neighborhood design has been retained during Kuwait's ongoing urbanization and ensures safety, security, and privacy for ideal suburban neighborhoods in the present day. However, plot owners are responsible for the design and orientation of houses, which must follow local zoning ordinances and building regulations on built-up areas, setbacks, building heights and projections, *etc*.,[6] It is worth noting the particular focus on privacy at the scale of the apartment housing unit in JA, as personalization, views, and sound insulation become important design factors, although they were not explicitly requested in the planning stage. A staggered building approach is adopted for vertical housing units to ensure the occupants of one building do not have visual access to their neighbors in the adjacent buildings. As such, privacy is Partially Considered at JA.

3.3.10 Imageability, identity, and sense of place

As posited by Ahmed (2017), imageability denotes the extent to which distinguishable features and activities, as well as architectural and urban design, provide a sense of identification and place for residents in a neighborhood that quality in a physical object which gives it a high probability of evoking a strong image in any given observer. It is that shape, color, or arrangement which facilitates the making of vividly identified, powerfully structured, highly useful mental images of the environment (Lynch, 1960). Imageability is supported by design elements such as the path, node, landmark, edge, and district that combine to convert urban spaces into places that feel familiar. Christian Norberg-Schulz (1979) considers the experiential, phenomenological elements of architecture in creating a sense of place. He claims that orientation and identification are key to achieving familiarity and a sense of place, a term he refers to as *genius loci*. Whether from an urban or phenomenological-architectural perspective, identification creates a sense of belonging for both residents and visitors to a neighborhood. It fosters safety and inclusion and ties space to memory and experience. It is facilitated by high urban density, compactness, mixed uses, accessibility, and environmental quality.

At JA, the elements of imageability and sense of place appear to have been supplanted by the government's programming requirements, infrastructure, and regulatory codes. At a large scale, these have produced spaces that people struggle to identify with. For one, the lack of landscape design in multiple roundabouts disorientates residents and visitors by rendering neighborhood streets and residential blocks generic. There are no public plazas or spaces for community gathering beyond those at the main commercial node and the "Green Fingers," which have already been abandoned or fenced off by private residents due to underdevelopment. The residents' protest at this lack of imageability is evident in their publicized requests for improved services in the area (AlAdala, 2021). Thus, imageability at JA is Not Considered.

3.3.11 Passive solar design

Any evaluation of solar design at the building scale must account for aspects such as built form, building design, the use of urban materials and surfaces, the availability of water and vegetation, traffic patterns, and street canyons. With neighborhood street widths of about 6 m, plotline-to-sidewalk setbacks that range between six and 8 m, and building heights of 15 m, the hot and dry climate is more likely to produce rather stagnant conditions that inhibit nocturnal radiative cooling in the neighborhood (AlKhaled et al., 2020) (Figure 9). This discourages walkability and prevents residents from lingering outside their homes for social interaction with neighbors. Meanwhile, the parking of automobiles on pavements and streets also contributes to urban heat gain due to the high thermal capacity. Cars moving through the neighborhood produce anthropogenic waste heat that is often not effectively ventilated out of the residential block by the morphology of the street canyon at an efficient rate. Table 2 demonstrates the limited effectiveness of JA neighborhood's passive solar design characteristics to meet the SUF criteria, which is apparently Not Considered in either design process or product.

4 Discussion

This process-to-product analysis has considered the design and construction of Jaber Al-Ahmed from the client, designer, contractor, and resident user perspectives, evaluating the extent to which JA's social housing meets the Sustainable Urban Forms criteria. As a *design product*, JA successfully fulfills one of the SUF criteria (Density), while the design partially considers nine categories (ranked by highest score: Privacy, Diversity, Mixed Use, Safety & Security, Accessibility, Mobility & Sustainable Transport, Choice, Greening & Environmental Quality, and Local Autonomy), and does not address two categories (Imageability and Passive Solar Design). Overall, JA is either fully or partially responsive to ten of the twelve SUF design principles examined. Analysis shows that the Design stage for JA was the most responsive to SUF criteria, followed by Occupancy, Planning, and finally Construction stage. To further enhance the ways that the SUFs might meet the State of Kuwait's social housing needs, our recommendations on social housing policy and *design process* are set out below:

1. Closer collaboration and a clearer direction are required from all government authorities involved during the initial planning

6 The latest version of building regulations and zoning ordinances does not seem to address this design component for 400 m^2 plots beyond the requirements for detached single-family villas described above.

phases. Under PAHW leadership, the consortium of ministries should strive to fully achieve the original vision or design concept. This requires all relevant authorities to coordinate fully with each other, provide their input to the process from an early stage, and budget for the resources needed to realize the design.

2. Increased interdisciplinarity is required among policymakers, planners, financiers, developers, architects, project operators, and any (sub-)contractors that participate in the design and construction processes, in a manner that avoids disrupting or distorting the original design concept.
3. Green spaces must feature in all future ToRs provided by the PAHW. Green spaces must be considered as infrastructural components that link communal spaces and increase walkability, imageability, and social interaction with the neighborhood. This is a crucial point to make since residents should move into their neighborhoods with parks and green spaces already established and matured.
4. Before commissioning projects, the PAHW must have an overall, comprehensive vision, philosophy, or approach that guides decision-making. The sustainability directive signed in response to the UN's 2030 Agenda is potentially one such approach. In addition, the PAHW should undertake follow-up evaluations of initiatives, using post-occupancy surveys, for example.
5. It is crucial to recognize the importance of participatory design practices and legitimize unplanned urban practices through environmentally responsive building regulations and community engagement.

Overall, this study does not propose novel approaches to designing sustainable social housing neighborhoods *per se*. However, it aims to support the continued reworking of sustainability measures already adopted in other parts of the world. Indeed, such measures are already evident in the PAHW initiatives at all scales, including the incorporation of sustainable technology in public buildings and dwelling units to meet renewable energy needs, the revision of building specifications and zoning codes, and the initiation of smart city design. While this singular case does not provide a generalized view of sustainable built environments, especially considering the nascent nature of this field in the Arabian Gulf and Kuwait in particular, it is one step towards understanding sustainable social housing in Kuwait. Generalizability in this case, including discussions and analysis of the Terms of References and design consultant contributions, as well as the presentation of diagrams, is particular to the JA site and the limitations of space and time.

In examining the process-to-product design procedure in the case of Jaber Al-Ahmed, no evidence was found of deliberate "greenwashing" at the state level, in the manner described by Elsheshtawy (2018). However, the rhetoric of sustainability is being engaged via partial commitments to both the international NUA and the 2030 Agenda. There is evidence of the "worlding" strategy used to gain the international recognition of developed countries: Kuwait's commitment to the 2030 Agenda is publicized while policymakers seem to lack concern for ecology at the local level. For instance, recent news about the state's venture into smart cities is one example of its commitment to sustainable living environments whose results remain unrealized in neighborhoods like South Saad Al-Abdullah.

Another demonstration of this trend is the latest decision by Kuwait Municipality to regulate landscaping and planting practices in open spaces in neighborhoods by issuing four-year permits (AlEnizi, 2020). This policy essentially allows plot owners to legally encroach onto public land by planting it for a limited time, thereby privatizing such spaces in an apparent effort to maintain what Crot (2013) describes as the "social contract" between the government and people. Ordinary urban practices need to be examined and legitimized by policymakers through design intent and building codes to fulfill aspects of choice at the local level. However, decision-makers must also avoid falling into the trap of the social contract that appeases citizens *in lieu* of effective governance measures that benefit the state. While this study marks the first steps toward examining SUFs in the Arabian Gulf, further research is required to assess local PAHW initiatives against SUF principles and the realization of sustainable social housing in the region.

This evaluation of one social housing neighborhood reveals that the impetus of design intentions may be eroded during the actual process of design in coordination with the client, and later, by the contractor. Project handovers may also decompose the original design intent or concept when various government authorities not directly invested in the project are expected to operate and maintain the properties and design features without prior involvement in the design phase. When these actors are disenfranchised, the project or product of the sustainable social housing initiative is much more likely to fail. Herein lies the paradox: the government's resource-intensive megaprojects (at the planning, design, construction, and occupancy levels) give way to resource-intensive management and life cycles in social housing (at the level of residents). Social housing policy must not only distribute land parcels and offer public services but should also promote a framework that fosters self-organized community building and allows the adoption of grassroots practices to achieve sustainability for all (Morgan and Talbot, 2000; Plumb et al., 2011; Wheeler, 2015). Moreover, further study on post occupancy and other social housing neighborhoods is required to gain a better understanding of the dynamics at play. Such research should also emphasize how each of the twelve SUF principles impacts the achievement of sustainable social housing.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by the Ethics Review Committee (ERC), Kuwait University. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

Author contributions

MA-A and SA conceptualized the project, developed the methodology, gathered literature, and acquired and analyzed data. MA-A was responsible for manuscript writing and producing photographic images and project delivery diagrams. SA produced analytic diagrams and graphics. All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Identifying the issues leading to residents' modifications in Bahraini subsidized housing units

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Research problem and purpose: Residents' modifications in subsidized housing are a widespread phenomenon in Bahrain. Households begin to modify their allocated residential units as soon as they receive them, resulting in financial burdens and an aesthetic loss of the uniform physical appearance. This research aims to identify the issues leading to residents' modifications in Bahraini subsidized housing units.

Materials and methods: Literature indicates that this phenomenon is closely related to resident behaviors. Thus, the study presents a conceptual framework that examines the similarities and differences in residents' behaviors in subsidized housing. Accordingly, the study employed the qualitative approach and was conducted in two phases. The first phase investigated common resident behaviors through structured interviews with twelve experts involved in the modification process. The second phase used the case study strategy with three selected cases from the East Hidd housing project to examine the different behaviors related to residents' lifestyles. It included on-site observations, plan analysis, and structured interviews with householders using the AIO approach.

Results: The findings revealed general and specific issues that lead to residents' modifications. The general issues represent common behaviors for most residents and are usually associated with the prior-occupancy stage. They include residents' preference for simple modern designs with spacious living rooms and bedrooms, trendy modern materials, and large windows; residents' need for sustainable housing units that incorporate all three aspects of sustainability, particularly the socio-cultural, which is related to factors like privacy, hospitality, and the aesthetics and distinction of houses; and the damages resulting from the improper practices of residents that mainly revolve around excluding the experts and involving the unqualified in the modifications process. The specific issues represent families' different behaviors and are usually associated with the post-occupancy stage. Those include residents' need to modify their houses according to their lifestyles, which appeared in the guest room, the courtyard, and the interior divisions of the extended bedroom.

Conclusion: Considering both issues while designing future projects helps create flexible units that satisfy the needs of the majority while allowing for modifications at any time. This, in turn, helps reduce and streamline the modification process.

KEYWORDS
transformations, alterations, residents' behaviors, sustainability, lifestyle, public housing, AIO

1 Introduction

Home is a haven for humans and a refuge from the outside world's noise (Bachelard and Stilgoe, 1994). It is the place that one can escape to, where he finds safety, comfort, and isolation (Dayaratne and Kellett, 2008; Jacobson, 2010). Thus, a home must meet one's needs, desires, and preferences (Jiwane, 2021). For this reason, the architect's role is based in the first place on the desires and needs of individuals. But what if the design of the house is unified for a group of people? How can the architect make it suitable for all of them? It will undoubtedly be challenging to achieve since each resident has different desires and perceptions. This fully applies to housing projects designed for a large group of people. Although housing projects are typically designed to meet the requirements of residents, they usually do not fully accomplish their needs and preferences (Ahmed and Othman, 2015). Further, responsible authorities are unable to provide a precise unit design for a wide variety of residents with different needs (Jiwane, 2021). Accordingly, most residents make various modifications to their housing units according to their passions and desires, leading to financial burdens (Natakun and O'Brien, 2009; Ahmed and Othman, 2015).

The phenomenon of residents' modifications is regular and widespread in housing units worldwide, including Bahrain, where residents begin to modify the designs of their housing units after receiving the keys (Saraiva et al., 2019). It is an inevitable continuous process influenced by sociocultural factors, evolving lifestyles and circumstances, human needs and behaviors, and economic and technological growth (Dayaratne and Kellett, 2008; Obeidat et al., 2022; Ozer and Jacoby, 2022). This means that this phenomenon cannot be stopped because every family has different needs, and a typical design cannot satisfy everyone's requirements (Jiwane, 2021). However, the modifications can be either reduced or facilitated in future projects (Chukwuma-Uchegbu and Aliero, 2022). Besides, studying the similarities and differences of subsidized housing designs is beneficial and aids in improving housing regulations (Ozer and Jacoby, 2022).

Despite the prevalence of this phenomenon, limited studies on residents' modifications in subsidized housing have been conducted in Bahrain. Furthermore, while the literature indicates a strong link between this phenomenon and residents' behaviors (Salman, 2016; Mahmood and Hussain, 2018; Sunarti et al., 2019; Aryani and Jentu, 2021; Obeidat et al., 2022), few studies have addressed residents' common behaviors during the modification process. Aside from that, relatively few researchers have examined the relationship between residents' diverse lifestyles and their modifications in subsidized housing. Consequently, this research aims to fill these gaps as a critical step in identifying the issues leading to modifications in Bahraini subsidized housing. This, in turn, contributes to improving the design of future housing units as it reveals the preferences and motivations of Bahraini residents in subsidized housing. It also contributes to reducing the modifications and violations. Besides, it aids in exploring the patterns of residents' modifications that assist in determining the particular needs of residents and setting guidelines for the design of future projects. In addition, this research is occasionally and regionally necessary since technology, social, and cultural factors impact residents' behaviors and lifestyles (Dayaratne and Kellett, 2008; Duffy, 2009; Ozer and Jacoby, 2022).

This paper is part of a broader, ongoing study for a master's thesis that aims to identify the issues leading to residents' modifications in Bahraini subsidized housing units. It focuses on the findings of 12 expert interviews and three case studies, whereas the master thesis expands on the research and includes a sample size of 20 experts and six case studies. Thus, the preliminary results are presented to a wider audience in this paper. In contrast, the master thesis presents a more thorough examination and comprehensive discussion. The study objectives are as follows:

- Determining residents' common behaviors in Bahraini subsidized housing units.
- Analyzing the patterns of residents' modifications.
- Studying the relationship between residents' modifications and lifestyles.

These objectives seek to answer the research question: What issues lead to residents' modifications in Bahraini subsidized housing units?

2 Literature review

2.1 Background

A subsidized housing project is a local government-provided program that consists of residential units for low-income residents (Freeman and Botein, 2002). The term 'Subsidized housing' is inclusive as it encompasses a variety of housing that is financially subsidized and granted by the local housing authorities (Ozer and Jacoby, 2022). Providing those housing projects is essential for societies because they significantly contribute to offering suitable accommodation and public services for low-income households (Drews, 1983). Subsidized housing projects also contribute to developing social and economic segments (Keith et al., 2011). This is owing to the massive scale of these projects and the use of standard designs, which reduces construction costs (Ozer and Jacoby, 2022). Subsidized housing units are generally small and consist of two or three floors (Stoloff, 2019). They are provided with general needs and standard regulations (Reeves, 2005). Since these units follow standards and universal characteristics, their designs are typical Since these units follow standards and universal characteristics, their designs are typical (Salman, 2016). However, these standards differ from one country to another depending on the socio-cultural aspect (Ozer and Jacoby, 2022).

In Bahrain, the growing urbanization and overpopulation put severe stress on the Ministry of Housing (MoH) to accelerate the construction of housing projects and fulfill the current and future public demands (Al-Saffar, 2014). Consequently, the MoH has presented significant efforts in the housing sector by developing numerous housing programs in various locations across the country (Al-Khalifa, 2015). Thus, the Kingdom of Bahrain is considered one of the Arab Gulf countries with conspicuous success and prosperity in the housing sector due to its ability to accommodate rapid urbanization and residential development (Al-Saffar, 2014). Subsidized housing projects are among the fundamental policies of the MoH, which are accomplished either through extending existing cities or establishing entirely new ones (Al-Khalifa, 2015). The primary goal of those projects is to provide appropriate accommodations for low-income households (Al-Saffar, 2014; Al-Khalifa, 2015; Salman, 2016). Isa and Hamad towns, established between 1963 and 1984, are considered among the initial housing initiatives and significant achievements of the MoH (Hamouche, 2004; Al-Khalifa, 2015). Both of those housing developments provided residents with subsidized housing units and public services (Hamouche, 2004). Since then, the MoH has developed various housing projects in several regions throughout Bahrain (Al-Khalifa, 2015).

In addition to Isa and Hamad Towns, previous subsidized housing projects include Malkiya, Madinat Zayed, and Zallaq, while recent developments include East Hidd, East Sitra, Salmabad, and others. So, the literature indicates that subsidized housing is an urgent priority for societies since it offers suitable housing for low income families while also improving the social and economic sectors. It also shows that the housing units in these projects are characterized by unified designs and specifications, which drives residents to make various modifications.

2.2 Residents' modifications in subsidized housing

The process of modifications in housing units can be described in several terms, including housing transformations, extensions, adjustments, and alterations (Aduwo et al., 2013). The alterations in this process have various ways, like modifying housing requirements or improving their livability (Mohit et al., 2010). In other words, the modifications could be major related to the structure of the house, or minor, such as changing the color of the rooms (Obeidat et al., 2022). In addition, these modifications differ according to their legislation and location. For this reason, researchers have described this process with different definitions. For example, Chukwuma-Uchegbu and Aliero (2022) define it as occupants' responses to unfulfilled needs in standard housing units. Moreover, Natakun and O'Brien, (2009) describe it as remodeling internal and external spaces through a set of changes to the design and structure of the house to meet the particular family needs while also reflecting their tastes and personalities. Similarly, Aduwo, Ibem and Opoko (2013) claims that this process refers to the adjustments that inhabitants make to the layout of their housing units to meet their evolving demands and preferences. So, the process of resident modification is a significant phenomenon that occurs in subsidized housing all around the world. Therefore, it is essential to review it from both local and international perspectives.

2.2.1 International perspective

Several international studies have discussed the issue of residents' modifications in subsidized housing units. For example, Jiwane (2021) conducted a survey to investigate occupants' opinions and satisfaction with a housing project in Kanhapur village in India. The findings of this study show that dwellings were modified and altered by the occupants because they didn't meet their demands. Another study by Tipple (1999) examined the housing transformation in four different countries: Egypt, Bangladesh, Ghana, and Zimbabwe. The results clearly show that the selected case studies have a common issue of not having enough rooms for the residents, and the plot size is small, which led them to extend the space. The results further show that many new owners of subsidized housing units will expand their living spaces to make their homes more suitable for their lifestyles.

In addition, Natakun and O'Brien, (2009) investigated the common modifications made in one of the housing projects in Bangkok by analyzing the architectural plans and conducting interviews with its residents. The findings indicate that residents modified their homes by following common patterns, such as extending the front and back patios, living rooms, and roofs. The results also imply that the modifications made by residents reflect their preferences and emotional needs.

2.2.2 Local perspective

The phenomenon of residents modifications has been discussed in some local research. Salman (2016) elaborates on this indicating that Bahraini residents adjust their housing units as soon as they move in to meet their requirements and reflect their identities. Salman attributes this to the typical layout of housing units that do not suit the different tastes of inhabitants. Moreover, Alkhenaizi (2018) claims that numerous households in Bahrain expand their houses to provide accommodations for their adults.

Even though this phenomenon is prevalent in subsidized housing in Bahrain, few studies have been conducted on it. One of the studies was conducted by Saraiva, Serra and Furtado (2017) who analyzed and compared the spatial configurations of traditional and subsidized housing in Bahrain. According to Saraiva, Serra and Furtado (2017), analysis indicates that gender segregation, one of the fundamental social values of the Bahraini society, is missing in the new subsidized housing. Furthermore, Saraiva, Serra and Furtado (2019) demonstrate that several modifications were made to the units' layouts of the Samaheej project, including structural transformations, connecting the setbacks with the indoor and extending spaces. The study also confirms that when residents receive their houses, they immediately modify the functional distribution of spaces, structure, and style.

So, the international and local reviews show that residents' modifications differ from one region to another. This implies that the process of modifications in subsidized housing is firmly based on residents' behaviors.

2.3 Residents' behaviors in subsidized housing

Subsidized housing residents make various modifications to their units based on specific preferences. For example, they modify their dwellings to enhance their living conditions while also meeting the emerging demands of their family members (Salim, 1998). They also aspire to provide additional spaces that satisfy their housing requirements and activities (Aduwo et al., 2013). Furthermore, housing transformations enable residents to personalize their homes to meet their desires and expectations (Mohit et al., 2010). Thus, residents' needs and requirements are linked to several aspects. Accordingly, these aspects shape residents' behaviors, which, in turn, affect the design of subsidized housing units. Obeidat et al. (2022), for instance, argue that the alterations made to housing units are attributed to the spatial behaviors of residents. Similarly, Sunarti et al. (2019) found that occupants' changing behavior led to a transformation in low-income housing. Mahmood and Hussain (2018) support the same point, affirming that adjustments to physical housing spaces reflect the inhabitants' behaviors. This indicates that occupants' behaviors play a fundamental role in the process of modifications in subsidized housing. Therefore, it's essential to study the aspects associated with residents' behaviors and their influence on the design of housing units (Obeidat et al., 2022). The literature discusses the following aspects:

2.3.1 Motivational factors behind residents' modifications

Studies have discussed several factors influencing residents' behaviors and practices in subsidized housing. One of these essential aspects is socio-cultural. House designs and functions express cultural and social principles and concepts (Lawrence, 2019). Indeed, families evaluate housing conditions based on the extent to which family and cultural norms are employed (Morris and Winter, 1975). Not only that, if the housing does not meet those standards, it frequently leads to residents' dissatisfaction (Morris and Winter, 1975). Ozer and Jacoby (2022) have found that sociocultural norms fundamentally influence housing designs and standards. Besides, they also emphasize that sociocultural norms determine the differences in requirements for subsidized housing designs. Furthermore, Obeidat, Abed and Gharaibeh (2022) have discussed the significance of privacy as a basis for modifying public housing design. They confirm that the modifications made to housing designs are based on sociocultural norms.

On the other hand, economic development and surrounding circumstances influence residents' behaviors, which are reflected in subsidized housing modifications. For example, Aduwo, Ibem and Opoko (2013) indicate that various interconnected factors, including socioeconomic trigger housing alterations. Besides, Al-Saffar (2014) argues about the impact of the developing economy on the living standards of Bahrain residents. Sunarti, Syahbana and Manaf (2019) agree about the same view, claiming that economic status impacts the transformation of housing units. Ozer and Jacoby (2022) also support this, demonstrating that the COVID-19 pandemic has generated new residential demands and aspirations. In addition, Alkhenaizi (2018) has discussed how Bahraini residents' behaviors have changed due to globalization. According to Alkhenaizi (2018), many households currently live in modest, modern-style homes rather than the larger ones that used to house generation upon generation. Similarly, El-Haddad (2003) has discussed the same subject in GCC countries, indicating that households migrated away from courtyard houses and are moving towards contemporary ones that encourage individual expression.

This means that residents have particular housing preferences over time. It also indicates that residents' modifications in subsidized housing reflect those preferences. For this reason, designers and developers must be conscious of consumers' changing demands and preferences and stay current with the recent trends in housing designs (Lee, Carucci Goss and Beamish, 2007; Wardhani et al., 2020). Thus, housing modifications keep changing over time, resulting in new trends that necessitate ongoing research (Nwankwo et al., 2014).

So, investigating residents' common modifications that reflect their housing preferences and the reasons behind them provide a comprehensive understanding of the major issues driving residents' modifications in housing units. Several studies have discussed those concepts. For instance, Nwankwo et al. (2014) investigated the nature of modifications made by most residents and the reasons behind them. Chukwuma-Uchegbu and Aliero (2022) also surveyed the design factors needed for future housing projects by examining the nature of residents' post-occupancy modifications. Similarly, a study by Obeidat, Abed and Gharaibeh (2022) was conducted to determine transformation forms for a public housing project.

2.3.2 Implications of residents' modifications

While modifications to housing units increase residents' satisfaction, they negatively impact the building's efficiency and sustainability (Aduwo et al., 2013; Ahmed and Othman, 2015). This occurs due to residents' incorrect behaviors and habits and improper practices during the modification process, triggering numerous problems and risks. Makachia (2005) investigated the transformations of a Nairobi city housing project and discovered that they influenced the aesthetic aspect. Landman has further found that the modifications created shambles, reduced the intended convenience and privacy, decreased interior ventilation for the interiors, and limited leisure and social spaces. Moreover, Aduwo, Ibem and Opoko (2013) propose developing a basic housing scheme that would allow residents to modify their housing units in an organized and thoughtful way while minimizing negative consequences. For this reason, Abdellatif and Othman, (2006) believe it is essential to pinpoint flaws and mistakes in residents' modifications in low-income housing projects to prevent duplicating them and enhancing their quality in subsequent projects. Furthermore, Abdellatif and Othman, (2006) conducted a study on a low-income housing project in Abu Dhabi, United Arab Emirates, investigating the mistakes and negative impacts of residents' modifications. The findings of this study have revealed that these mistakes resulted either from wrong design decisions or construction flaws caused by the residents through the modification process.

This issue also exists in subsidized housing projects in Bahrain. There have been several infractions of building modifications in housing projects, including wrong engineering practices that resulted in cracks in the walls of the units, water leaks, and faulty electrical connections that may lead to fires (AlBilad, 2020). Many residents attempted to fix the illegal practices, but they encountered difficulties due to the seriousness of those infractions and the high financial cost (AlBilad, 2020). Besides, other residents also had difficulty obtaining building permits because they were not adhering to the regulations (AlBilad, 2020). This indicates that, these housing damages and negative implications of the modifications they made to their dwelling units result from the wrong behaviors and mistakes they made during that process (Abdellatif and Othman, 2006).

Thus, mistakes and illegal practices are considered part of the common wrong and risky behaviors many residents make during the modifications process in subsidized housing due to their scanty experience in this field. This emphasizes the importance of involving experts and engineers in the modification process, which many residents ignore (Nwankwo et al., 2014). As a result, experts, such as professional engineers and designers, must understand residents' behaviors because their primary role is to serve and meet their needs. Therefore, the process of residents' modifications, motivations, and consequences probably vary among nations (Aduwo et al., 2013). In other words, residents of subsidized housing in a particular region share common behaviors and practices. However, there are some differences in residents' behaviors related to their lifestyles that experts must be aware of and account for in every modification they make, as they differ from one family to another and from one house to another.

2.3.3 Lifestyles and the AIO approach

The concept of lifestyle is usually employed in studies of users' behaviors and preferences (Lee, Carucci Goss and Beamish, 2007). Scholars have heatedly debated and described this concept in a variety of ways. For instance, Plummer (1974) described it as a way of life that deals with many issues intimately connected to individuals' attitudes in their daily life and work. Reichman (1977) considered it an individual's behavioral reaction to socioeconomic disparities. Similarly, Veal (1993) defined it as a distinct pattern reflecting interpersonal or social behavior. Furthermore, Jensen (2009) believed that lifestyle should not be viewed as a fixed thing because it is associated with mutable habits, implying that lifestyle changes with time. This indicates that lifestyle research is critical in understanding users' behaviors.

Recent studies focus on lifestyles as a representation (Aduwo et al., 2013) of behavioral orientations and patterns (Zhao and Lyu, 2022). This is reflected in residents' modifications to their units, resulting in various design patterns. Consequently, this suggests a relationship between residents' modifications in housing units and their lifestyles. According to Aduwo, Ibem and Opoko (2013), residents modify their housing dwellings because they do not meet their demands and lifestyles. Besides, Mirmoghtadaee (2009) highlights the link between the modifications to housing forms and residents' lifestyles, indicating that the components of the residential units represent the dominant lifestyle based on sociocultural attributes. Mirmoghtadaee (2009) further emphasizes that residents alter their environments to suit their needs and lifestyles.

Diverse variables can influence users' lifestyles, including income, fortune, age, socioeconomic factors, material status, presence of children, place, and interests (Beamish, Carucci Goss and Emmel, 2001). The AIO approach is a measurement tool developed to study users' lifestyles by examining those variables (Zhao and Lyu, 2022). It was first devised by Wells and Tigert (1971), focusing on three dimensions: users' activities, interests, and opinions. These dimensions are associated with how people utilize their leisure time, their areas of interest, and their perspectives (Zhao and Lyu, 2022). Later, Plummer (1974) expanded the AIO approach by including demographics. According to Plummer, demographic is related to several characteristics, including age, family size, and occupation. As a result, the AIO approach has four dimensions linked to specific aspects.

2.4 Sustainability and subsidized housing

Sustainability is one of the most significant issues of the current time in the architectural field. It's not merely a trend but a massive step toward healthier environments and better lifestyles (El-Ghonaimy, 2010; Abouelela, 2021). It's a development that addresses the demands of both current and future generations (Kirkby et al., 1995). Sustainability incorporates crucial characteristics that most inhabitants strive for in their home designs combined in three pillars: Social, Economic, and Environment. Implementing those pillars in housing projects enhances their performance and satisfies residents' needs and requirements (El-Ghonaimy, 2010; Ibrahim, 2020). In fact, subsidized housing standards integrate social, cultural, and economic aspects associated with residents' common behaviors and lifestyles (Ravetz, 2001). Since these aspects are the pillars of sustainability, it implies a relationship between residents' modifications in subsidized housing and sustainability. In other words, residents of those houses behave according to sustainability aspects. Numerous studies have discussed the significance of sustainability for housing projects (Abdellatif and Othman, 2006; Talen and Koschinsky, 2011; Ibrahim, 2020; Atália et al., 2022).

2.5 Literature gaps

Based on the literature review, the process of residents' modifications in subsidized housing is a common phenomenon locally and internationally and is mainly associated with residents' behaviors. However, although the literature has extensively discussed residents' behaviors in subsidized housing, few have addressed the similarities of these behaviors in the process of modifications. Besides, residents' common mistakes and incorrect practices were not adequately highlighted despite the seriousness of the matter, its negative impacts on the buildings, and its widespread prevalence in subsidized housing worldwide and in Bahrain. Similarly, few studies have been conducted on the differences in behaviors related to the lifestyle of subsidized housing residents, notwithstanding the literature indicating an association between the modifications and lifestyle. Despite the AIO approach's efficiency in studying and comprehending users' lifestyles and behaviors (Zhao and Lyu, 2022), only a limited number of studies have applied it in housing research in general and residents' modifications in particular.

Therefore, this study seeks to fill these gaps to answer the research question: what are the issues that lead to residents' modifications in Bahraini subsidized housing units?

3 Materials and methods

3.1 Conceptual framework

The literature and recent studies like (Atália et al., 2022; Chukwuma-Uchegbu and Aliero, 2022; Obeidat et al., 2022; Ozer and Jacoby, 2022; Zhao and Lyu, 2022) revolve around the following key points:

- Residents of the same region share similar behaviors and practices because they share the same customs and traditions. These common behaviors, however, can change over time and are influenced by technological advancement and economic growth.
- Residents' common behaviors during the modification process in subsidized housing reflect their housing

preferences toward recent trends, common motivations for the modifications, and residents' common mistakes and incorrect practices.

- Residents' behaviors differ in some ways due to the unique lifestyles of each family. This can be seen in the modifications that residents make to the design of their housing units based on their particular needs and perceptions, resulting in various design patterns.
- There is a relationship between residents' modifications and sustainability aspects. These aspects represent the common motivators for residents to make modifications, and they vary by region. Therefore, it's necessary to investigate which aspects are most required for housing residents.

So, residents of subsidized housing in the same region have similarities and differences in their behaviors and practices in the modification process. On the one hand, similarities represent residents' common behaviors and are associated with three categories: current common and repeated modifications reflecting most residents' inclinations and preferences, common motivations behind modifications, and common improper practices. On the other hand, differences represent residents' distinct lifestyles and are linked to four dimensions: Demographics, Activities, Interests, and Opinions. Accordingly, as an initial step toward answering the research question, which seeks to identify the issues that led to residents' modifications, this study develops a conceptual framework that investigates the similarities and differences in residents' behaviors in subsidized housing (Figure 1). Research investigations into this field are limited, as only a few studies have examined the similarities and differences in housing designs (Chukwuma-Uchegbu and Aliero, 2022; Ozer and Jacoby, 2022).

3.2 Research methodology

The research is ethnographic and exploratory; it explores the issues behind residents' modifications in subsidized housing units in Bahrain. According to the conceptual framework described earlier, this necessitates gathering comprehensive and in-depth data about residents' common behaviors and lifestyles. Therefore, the research employed a qualitative methodology using two primary methods: qualitative interviews and a case study strategy, which was carried out in two phases as follows:

- The first phase investigated the similarities in residents' behaviors in Bahraini subsidized housing. Structured interviews were conducted with experts involved in the modification process from various engineering and interior design offices throughout Bahrain, including architects, interior designers, and civil engineers. The study used snowball sampling, a non-probability purposive sampling technique, to select the experts. Although the literature has emphasized the importance of experts in the processes of residents' modifications, only a few research in the field have used them as a study sample (Abdellatif and Othman, 2006; Sunarti et al., 2019). Experts were asked about the most common modifications, motivations, and mistakes relating to the resident modifications process. During the interviews, the experts expressed their enthusiasm for the subject at hand, emphasizing its significance in light of the current prevalence of this phenomenon among Bahraini subsidized housing residents. This method, however, was insufficient for exploring all of the issues underlying the modifications because it only revealed issues related to residents' common behaviors. Thus, a second, more focused phase of data collection was carried out to comprehend the issues concerning residents' lifestyles.
- The second phase used the case study strategy to examine the differences in residents' behaviors in Bahraini subsidized housing. According to the data gathered during the first phase of expert interviews, the East Hidd project is one of the housing projects with the most resident modifications. Consequently, the sample was chosen from this project with the assistance of the interviewed experts; they were asked to propose cases for modified houses in the East Hidd project, and a list was created based on their suggestions. Then, three

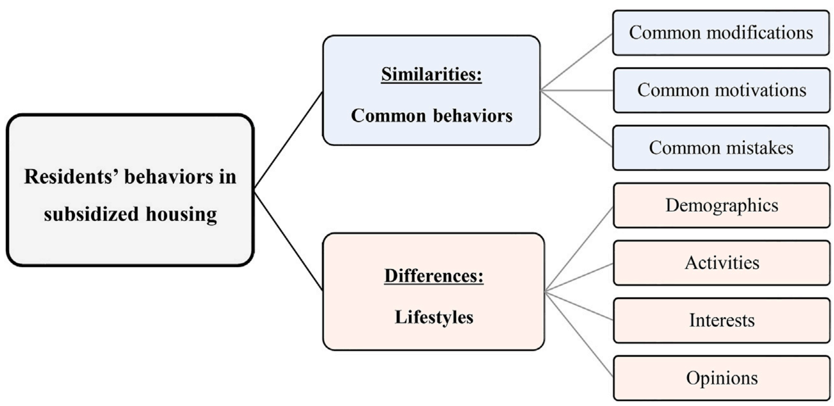

FIGURE 1
Conceptual framework.

case studies were selected using a convenient sampling technique according to residents' availability and readiness to participate in the research. Different research tools were used in the case study strategy. First, after obtaining permission from householders and getting their signatures on consent forms, on-site observations were conducted, which involved visiting the sites of the cases and documenting the observations with notes and photographs. It should be noted that 3D perspectives were used to document the modifications in private spaces like bedrooms where photography was not permitted. Several studies in the field have also used the observation tool (Jiwane, 2021; Chukwuma-Uchegbu and Aliero, 2022; Obeidat et al., 2022). During site visits, original plans were utilized to help understand the modifications made. After that, both the original and modified plans of each case study were analyzed by drawing them in AutoCAD and coloring the altered zones to aid in identifying the different design patterns of residents' modifications. Various studies have investigated the patterns of residents' modifications and used the plan analysis tool (Aduwo et al., 2013; Aryani et al., 2015; Alkhenaizi, 2018; Obeidat et al., 2022). The last tool used in this phase was structured interviews with householders. For each case study, an interview was conducted with one of the householders to investigate the relationship between the family's lifestyle and the modifications they have made. The AIO approach, which has four dimensions—demographics, activities, interests, and opinions—was used as the interview instrument. A recent study emphasized the significance and efficacy of this approach in examining lifestyles (Zhao and Lyu, 2022). However, limited studies used it in housing research (Lee, Carucci Goss and Beamish, 2007; Shafiei et al., 2010).

The methods used in both phases were cautiously chosen to contribute to filling the gaps identified in the literature review. In the first phase, expert interviews were conducted to fill the gaps related to the scarcity of data collected from experts on this subject and the lack of discussions on residents' mistakes during the amendment process. The second phase addressed the gap caused by the absence of lifestyle studies and the AIO approach in housing research. So, the research methodology contributed to collecting sufficient information about residents' similar and different behaviors regarding the subsidized housing modification process. This, in turn, contributed to achieving the research objectives and providing clear and comprehensive answers to the research question (Figure 2). The methodological triangulation strategy used in data collection, which involved various data sources and methods, helped ensure the study's validity and reliability. It also enabled a more robust and subtle interpretation of the findings and a more thorough comparison. The Research and Scientific Publications Committee gave its approval to the paper.

4 Results

4.1 Phase 1: interviews with experts

Findings of this phase revolved around three categories: Residents' common modifications in Bahraini subsidized housing, the common motivations behind them, and the common mistakes that residents make in this process. So, based on experts' responses, the data collected about each category were classified into different themes as follows:

4.1.1 The common modifications

This category is related to the housing preferences of residents. It includes the following themes:

4.1.1.1 Spaces

Interviews revealed that the most common modifications residents make in Bahraini subsidized housing are related to space. According to interviewee #4, the spaces of housing units are insufficient for fulfilling the demands of family members. Besides, "small spaces do not fulfill the requirements of the eastern Bahraini family," as interpreted by interviewee #6. Most interviewees also emphasized that the expansions were mainly made to the living rooms. This was confirmed by interviewee #2, claiming that "it is always requested to expand the living room hall to include a sitting area for female guests."

In addition, the living room has been expanded in various ways. For example, some residents increase its size by combining it with

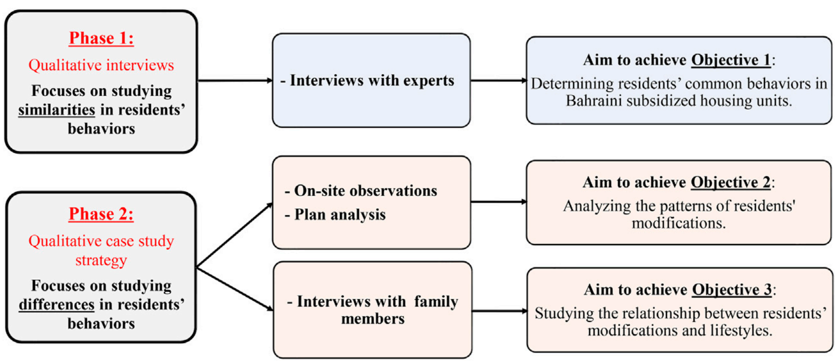

FIGURE 2
Research methodology.

the space of the guest room (Majlis). Another option, as demonstrated by interviewee #4, is to open the kitchen: "Clients frequently expand living rooms by removing walls and converting closed kitchens into open ones, resulting in a larger living room with a dining area." Some residents also expand it by using a portion of the garage space, which is an illegal practice, as highlighted by interviewee #6. Residents also use the same technique to expand the guest room, which is another illegal practice. Interviewees also indicated that residents make bedroom expansions, primarily by removing the balconies from the master rooms and using their spaces, as explained by interviewee #1. Moreover, extensions may also include the house's main entrance lobby because "it reflects the taste of the households," as argued by interviewee #4.

Furthermore, not only extensions but additions are also among the modifications associated with spaces. As evidenced by the interviews, one of the essential additions for the residents is the addition of an external kitchen. Interviewee #2 emphasized, "An exterior kitchen is always necessary to isolate the odors from the rest of the house." Likewise, interviewee #6 added, "The outdoor kitchen is essential in eastern homes because families use it daily for cooking." Additions may also include bathrooms and dressing rooms for first-floor bedrooms. This was emphasized by most of the interviewees, including interviewee #3, who stated, "Some customers desire more bedrooms and individual bathrooms for every room." Besides, specifying a space for the elevator is also among the recent common modifications, as highlighted by interviewee #4, "Most of those who build a third floor consider adding an elevator." In addition, most Bahraini residents need to add a third floor, as stated by the interviewees. Interviewee #4 confirmed this, "Most of the residents build a third floor, which usually contains the maid's room and the laundry room."

Besides that, interviews also revealed that residents use the outdoor spaces to create private gardens and shaded seating areas. Interviewee #3 explained, "Even if it is a small area, residents believe it must be present." Interviewee #1 also claimed that most residents prefer "adding shaded sitting areas or a pergola to the backyard." Furthermore, interviewee #4 added, "Sometimes residents request to expand the duct to 4 m in length and 3 m in width so it can be used as an indoor garden." Interviewee #4 further indicated that residents also request to create gardens on their units' roofs and "usually prefer to include pergolas, planting areas, and a barbecue area."

4.1.1.2 Materials

Modifying the materials, whether related to the interior design of housing units or the facades and outdoor spaces, is another modification performed by the residents. The interviews showed that the residents have certain common choices in this regard. Most residents, for example, prefer installing gypsum ceilings indoors because, according to interviewees, this material comes in various forms and sizes, including those resistant to temperatures and humidity, commonly used in kitchens. It is also durable and easy to install. Furthermore, most of the interviewees agreed that the substitute materials for the original ones are commonly used due to their lower cost and wide range of options. These include "WPC wood and PVC marble boards, which residents prefer to use mainly on the ground floor, particularly in the spaces that guests use, such as the main entrance, living rooms, and Majlis.", claims interviewee #4. This also applies to the floorings where "Ceramic and Porcelain are preferred as finishing materials instead of pricy ones," as indicated by interviewee #3. Interviews also demonstrated that residents incorporate contemporary materials like glass, wood, and aluminum into their exterior facades. In addition, for outdoor spaces, residents prefer using artificial grass instead of natural ones, which requires more maintenance, as emphasized by interviewee #10. Finally, regarding the colors, "Clients prefer neutral-colored paints," according to interviewee #11.

4.1.1.3 Housing components

Interviews indicated that there are common modifications related to housing components. They include enlarging the sizes of the living room windows facing the backyard. They also include expanding the windows on the main façade, which is illegal. Besides, interviewees confirmed that some residents raised the height of the parapet wall, and others increased the height of the external fence to obtain privacy. Not only that, but some residents also "add a shed to the living windows overlooking the backyard to provide privacy," as added by interviewee #12. Regarding lighting systems, interviewees agreed that residents have specific preferences mostly related to modern and trendy styles and techniques. According to interviewee #12, "There is an increasing demand for installing the magnet-track lighting system in subsidized housing units." Residents also prefer "adding hidden lighting to the ceiling," as claimed by interviewee #1.

So, residents' common modifications in Bahraini subsidized housing units revolve around three themes summarized in Table 1.

4.1.2 The common motivations

This category is related to the dominant reasons behind residents' modifications. It includes the following themes:

4.1.2.1 Social aspect

The interviews showed that residents made many modifications based on the social aspect. For example, most of the residents made expansions in their housing units because their sizes do not accommodate the needs of the residents and the number of family members. This was confirmed by interviewee #4: "Since the Bahraini family gathers every weekend, most families require a larger living room that overlaps with the dining room rather than isolating each space separately." Another motivation for residents' modifications is related to the future circumstances of family members. Interviewee #2 also explained this point, "Indeed . . . one of the children will eventually settle in the family home, and he will, of course, require some privacy."

In addition, most interviewees also emphasized that residents usually modify the façade of their housing units. According to interviewee #3, residents modify their façades "due to its rigidity and monotony." Moreover, interviewee #1 highlighted that residents modify facades "because they are typical in style and formation due to mass production, which creates confusion in finding the house's location or describing its' address." Interviews also clarified that privacy is another motivating factor behind the modifications. The privacy modifications, according to interviewee #10, include designating one guest room for men and another for women. Interviewee #10 further demonstrated that each family member

TABLE 1 The common modifications of Bahraini residents in subsidized housing.

Spaces	Materials	Housing components
• Expanding the living room	• Installing gypsum ceilings	• Enlarging living room windows
• Expanding the bedroom	• Using substitute materials like WPC wood and PVC marble for walls	• Enlarging the main façade windows
• Expanding the main entrance lobby	• Using Ceramic Porcelain for flooring finishes	• Raising the parapet wall and external fence
• Addition of an external kitchen	• Using simple modern materials with neutral colors	• Using a magnet-track lighting system
• Addition of bathrooms and dressing rooms for bedrooms	• Using neutral-colored paints	
• Addition of an elevator	• Using glass, wood, and aluminum cladding for exterior façades	
• Addition of a third floor containing a maid's room and a laundry room	• Using artificial grass for the outdoor spaces	
• Addition of shaded seating areas to the backyard and roof		

needs to have their own space. Furthermore, interviewees argued that residents are concerned about the aesthetics of their homes and how guests perceive them, and they consider it a critical reason for making modifications. Interviewee #4 claimed, "Residents usually modify the ground floor to make it suitable for guests only." Interviewee #11 explained, "Sometimes modifications are just luxuries and not a real need."

4.1.2.2 Economic aspect

As interviews showed, the economic aspect plays an integral role in the modification process, and it's one of the fundamental concerns for Bahraini residents in subsidized housing. For example, most residents seek cheap, high-quality materials requiring less maintenance, as most interviewees assured. Besides, residents' modifications are based on the needs of future generations as well as changing circumstances. According to interviewee #2, "the period of COVID-19 had a significant effect on the client's needs." This is exemplified by recent additions such as the gym and gaming room, as stated by interviewee #2. Other related modifications to this aspect include those aimed at saving energy in the home. Many residents, for instance, "tend to reduce the number of lights in the ceiling while still providing adequate illumination, resulting in lower lighting costs," as affirmed by interviewee #4.

4.1.2.3 Environmental aspect

As the interviews revealed, many of the modifications made by residents in their housing units are related to the environmental aspect. For example, as agreed by most interviewees, one of the most common requests is to enlarge the windows and doors to allow as much natural light and ventilation as possible to enter the interior spaces. Besides, interviewee #10 claimed that "Residents frequently include trees in their homes because they reduce heat." Furthermore, interviewees indicated that Bahraini residents pay close attention to their home's front and backyards, designing them uniquely with natural elements like plants and waterfalls. They also noted that residents frequently install larger windows overlooking these courtyards, making them feel more connected to nature, especially when waterfalls and plants are added. According to interviewee #1, "Some residents would have the desire to make glass facades overlooking the back garden." Moreover, as demonstrated by the interviews, modifications are influenced by the surroundings' geography. This was noticeable in the East Hidd subsidized housing project, where most residents "prefer to take advantage of the sea view by installing larger windows," as claimed by interviewee #4.

So, the common motivations behind residents' modifications in Bahraini subsidized housing units revolve around three themes summarized in Table 2.

4.1.3 The common mistakes

This category is related to residents' incorrect practices in the process of modifications. It includes the following themes:

4.1.3.1 Ignoring the role of experts in the modification process

Interviews revealed that residents make numerous wrong decisions during the process of modifications. Among these decisions is excluding the experts. According to the interviewees, most residents disregard experts' advice and insist on their own choices. Besides, they neglect to involve them in the process of modifications. This includes two cases: residents either make the adjustments independently or involve experts late in the process. This behavior results in many adverse effects. For example, "In the long run, not consulting a specialized office may result in structural flaws in these modifications." claimed interviewee #2. Besides, interviewee #6 highlighted that residents might "incorrectly install thermal, moisture, or water insulation materials." Furthermore, interviewee #6 also added, "These mistakes result in high electricity and consequences such as fires and trespassing on neighboring property." Not only that, but residents may also "remove a wall without realizing it is a bearer or direct support for the house . . . this has an impact on the building's safety in the future", claimed interviewee #5. Due to that, "most designers realize they need to make considerable changes to correct what the client has done. For example, they may need to break a wall, change the paint, or add new electrical outlets, increasing the costs and efforts and delaying the project delivery", as explained by interviewee #4. Thus, interviewees agreed that involving experts at

TABLE 2 The common motivations behind residents' modifications in Bahraini subsidized housing.

Social aspect	Economic aspect	Environmental aspect
• Housing unit sizes are not appropriate	• Residents' preference for affordable design solutions	• Residents' desire to feel connected with nature
• Residents' desire for distinction	• To keep up with the times and current housing design trends	• Bahraini residents' interest in front and back yards
• To obtain privacy	• To meet the diverse needs of today's generations	• To allow more natural light and ventilation into the house
• Residents' interest in the house's aesthetics		• Taking advantage of the natural environment that surrounds the housing unit

earlier stage help avoid these mistakes and violations and choosing the best solutions based on the client's needs and budgets.

4.1.3.2 Involving the unqualified in the modification process

Interviews revealed that a wide range of residents hire an unlicensed and inexperienced designers or contractors, which worsens and exacerbate the issue of modifications. The interviewers focused on the negative impacts and risks associated with residents' wrong behaviors. For example, interviewee #1 claimed, "it results in residents receiving a building violation, which prompts them to return to an engineering office to obtain a building permit without a breach, and the process is repeated." Besides, interviewee #1 further added, "Spending a lot of money on expansions and re-planning, which results in a budget deficit and residents will not have enough money for furnishing." Interviewee #4 also explained, "An unqualified contractor may misinterpret the design or start work without adequate detailed construction plans, follow-ups, or supervisory visits. As a result, many mistakes are made while making the modifications, such as installing the floors incorrectly."

4.1.3.3 Influence from other designs

Interviews revealed that this is one of the most prevalent behaviors in today's society, and social media has a big part in enabling it. This mistake occurs when residents copy designs from their neighbors or images found online. According to interviewee #2, "Due to the use of the Internet and social media, many ideas haunt the client's mind, which makes him unable to determine his priorities in choosing the design." Interviewee #6 presented an example of this case, stating that "if the neighbor builds something inside his house, the inhabitant imitates him or seeks the assistance of the same contractor in charge of the construction, whether he is experienced or not." The main reason behind these mistakes is that "Clients have high expectations for housing units in terms of the components used or the final design, which are out of proportion to the available space," as indicated by interviewee #9.

So, residents' common mistakes in the modification process in Bahraini subsidized housing units revolve around three themes summarized in Table 3.

4.2 Phase 2: case studies

The East Hidd is one of Bahrain's most recent subsidized housing developments. It's located in a new town in Muharraq Governorate. The project is expected to contain 2,827 housing units when it is finally completed (MoH, 2023). The Ministry of Housing offered different housing units, each with a slightly different layout. The areas of those units range from 240.85 to 256.337 square meters, and they all have two floors. Three case studies were chosen from this project to study the relationship between residents' modifications and lifestyles. The data collected in each case study was classified according to lifestyle dimensions and summarized as follows:

4.2.1 Case study 1

4.2.1.1 Demographics

The house is inhabited by six members: the homeowner and his wife, two sons, one daughter, and a maid. The couple is 38 and 36 years old, their sons are 17 and 6, and their daughter is 13. Their habitation period is 1 year and a half.

4.2.1.2 Activities

One of the most significant activities for homeowners is having breakfast and lunch with their children because of the nature of their work, which requires them to spend most of their time outside the home. Due to this, they reduced the size of the courtyard and added a dining space near the kitchen on the ground floor. As a result,

TABLE 3 The common mistakes made by residents during the modification process of Bahraini subsidized housing units.

Ignoring the role of experts in the modification process	Involving the unqualified in the modification process	Influence from other designs
• Making the modifications independently without involving experts	• Involving unlicensed offices	• Imitation of inappropriate social media designs
• Involving experts at a late stage in the modification process	• Involving an inexperienced contractor	• Imitating the designs of neighbors
• Disregarding experts' advice and insisting on their own decisions	• Hiring unqualified laborers	• Residents' unrealistic expectations and miscalculation of available space

FIGURE 3
Patterns of residents' modifications—Case study 1.

they also downsized the bathroom and designed a washing zone to serve the dining area. The living room is another critical space where family gatherings take place every weekend, which was the motive behind extending it toward the space provided for future expansions (Figure 3). The children's private tutors mostly use the guest room (Majlis) because it's a quiet space apart from the rest of the house. Besides, the homeowner uses it for hosting his friends once a week. So, to maintain the house's privacy, an external door was installed for the guest room, as explained by the interviewed householder. Additionally, the family members frequently use the courtyard's outdoor seating area on the weekends during the months when the weather is agreeable, where they can relax, barbecue, and enjoy the view of the waterfall and the plants they have sown (Figure 4). They also use it for family gatherings, particularly during Ramadan. In addition, another activity preferred by the homeowners is the use of the sitting room in the first-floor bedroom, which they designed specifically for their needs by expanding its area and dividing it into two zones: one for the bed and the other for seating with a TV, or "a home cinema," as the house owner described it (Figure 5).

4.2.1.3 Interests

The couple is concerned with the aesthetics of their home, which influences their selection of furniture, materials, colors, and finishes. Besides, because their budget is limited, they were looking for affordable and aesthetically pleasing solutions. However, they prioritize some preferences, even if expensive, such as the safest electrical sockets, floors, and furniture to ensure they last longer. As for the lighting, they provided a low-

FIGURE 4
Courtyard—Case study 1.

FIGURE 5
The expanded bedroom (3D)—Case study 1.

cost option that also looks beautiful because, for them, it is one of the items that can be easily replaced, regardless of its quality. The householder interviewed confirmed that he took special care of the entrance, hall, and Majlis because they are "the address of the house" where guests are welcomed. As a result, he employed high-priced and high-quality materials in these areas, such as foam and dyeing. The homeowners are also interested in home gardening, as they sow plants, roses, and fruit trees in the courtyard. They are also interested in nature, so they have installed an additional glass door in the living room facing the courtyard to allow more natural light and ventilation to enter the indoors and provide an aesthetic view.

4.2.1.4 Opinions

The interviewed householder asserted that he is delighted with all of the changes because he believes they have made the house

FIGURE 6
Patterns of residents' modifications—Case study 2.

FIGURE 7
Glass door overlooking the courtyard—Case study 2.

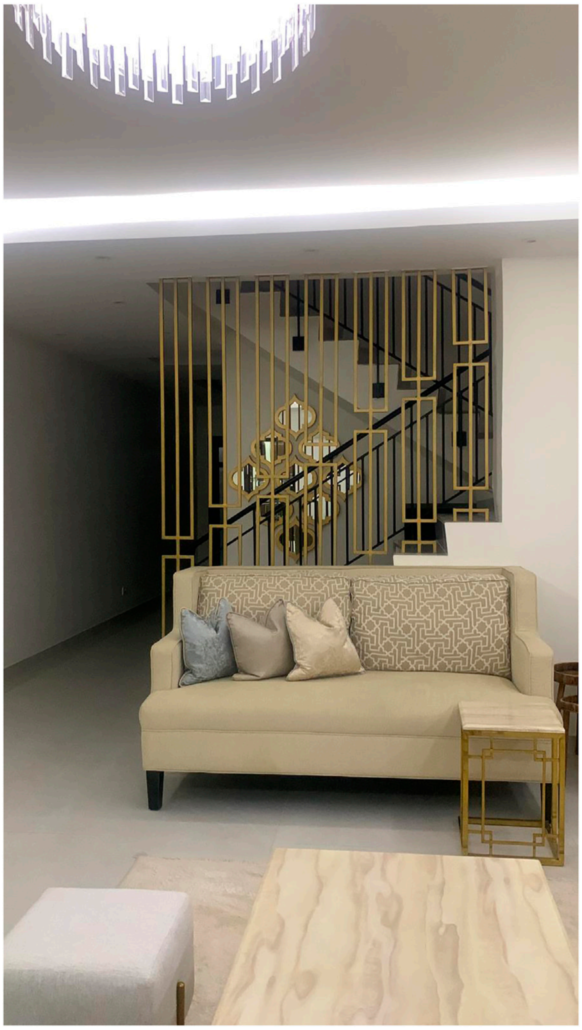

FIGURE 8
Golden-colored aluminum partition for the staircase—Case study 2.

better suited to the needs and desires of family members. He also noted that the modifications made the house look more beautiful in keeping with the modern style, indicating their interest in recent trends, as most subsidized housing residents prefer this style. However, the householder admits that he overspent on decoration and luxuries, saying, "I should have saved this amount for necessities before spending it on decoration."

4.2.2 Case study 2

4.2.2.1 Demographics

The house is inhabited by four members: the homeowner and his wife, one son, and one daughter. The couple is 39 and 45 years old; their son is 15, and their daughter is 14. Their habitation period is 3 years.

4.2.2.2 Activities

The house owners spend most of their time at work while their children are at school. For this reason, the time they spend at home is for "meeting to dine," as described by the interviewed householder. Thus, having a dedicated dining area is critical for them, so they expanded the living room to accommodate this need (Figure 6). Furthermore, the homeowners rarely have guests or family gatherings. Hence, they are unconcerned about the guest room and do not use it regularly; as the interviewed householder stated, "it would be better if the guest room's space were combined with the living room in the future." The householder also confirmed that family members frequently use the living room to gather and watch TV together on weekends or after work. In addition, cooking and baking are regular activities for the housewife, which is why the kitchen was expanded. Not only that, but the housewife also enjoys spending her free time reading stories and novels in a quiet area with a view of the outside, is exposed to sunlight, and is connected to nature. Therefore, the main bedroom was enlarged to accommodate this, and a sitting area was added, including a designated reading corner.

4.2.2.3 Interests

One of the elements that the homeowners are interested in is large windows that allow plenty of natural light and sunlight in. As a result, they enlarged the window and installed a glass door overlooking the courtyard to provide a stronger connection with nature (Figure 7). It is also important to them that the spaces are spacious, even if they do not have family gatherings, because this provides them with comfort when moving around, as described by the interviewed householder. They are also concerned with the aesthetic aspect and the quality, even if the cost is higher, so they removed the wall next to the staircase and replaced it with a golden-colored aluminum partition to provide an aesthetic to the living room (Figure 8). In addition, gypsum ceilings with concealed lighting were installed in most of the rooms. It is also critical for homeowners to achieve comfort in the home by customizing it to their preferences, even if it comes at a cost. For example, the housewife is interested in modern house designs that are more spacious and have large windows that connect to the outside. She is also interested in fashion and makeup and prefers having her own space in her bedroom. As a result, she considered these requirements when expanding her bedroom, which she describes as a separate apartment. Thus, the bedroom includes spaces for different functions: a seating area for reading and a dressing area with a makeup corner, precisely what the housewife desired. Since the daughter is also interested in fashion, just like the mother, her bedroom was expanded to accommodate this desire.

4.2.2.4 Opinions

The homeowners are not completely satisfied with the modifications because, for example, they discovered after experiencing the modified spaces that the guest room is underutilized. Furthermore, the interviewed householder confirmed that they wished to close off the area in front of the entrance door but could not do so because it is illegal. They also wished to replace the windows with larger ones. Since the homeowners do not benefit from the guest room and they rarely use it, they want to open it up to the living room in the future. Besides, after enlarging the living room, the area of the ground floor courtyard (garden) became relatively small, so one of their plans is to add a garden on the roof. They also intend to build an entire floor for the son when he is older. In the opinion of the homeowners, future housing projects should have more spacious interiors.

4.2.3 Case study 3

4.2.3.1 Demographics

The house is inhabited by six members: the homeowner and his wife, their son, their daughter, their grandmother, and their uncle. The couple is 31 and 36 years old, their son and daughter are 10 and 8, their grandmother is 70, and their uncle is 54. Their habitation period is 2 months.

4.2.3.2 Activities

One of the essential activities for homeowners is family gatherings on weekends. So, the homeowners took advantage of the space available for future expansion, constructing a living room for family gatherings instead of using the small existing one, according to the interviewed householder (Figure 9). They also used a portion of the courtyard space to construct a bathroom adjacent to the living room, with a ventilation space behind it. As the interviewed householder explained, "the living room is used not only for family gatherings but also for dining, and the children use it to play and study." Accordingly, the homeowners expand the living room since it serves as the primary gathering and activity space (Figure 10). The guest room is typically used when male

FIGURE 9
Patterns of residents' modifications—Case study 3.

FIGURE 10
The expanded living room—Case study 3.

guests, such as friends of the husband or uncle, arrive while women sit in the newly built living room. The homeowners are very concerned with both gender segregation and privacy. As it is difficult for the grandmother to ascend to the first floor, the old living room was replaced with a bedroom for the grandmother. The old living room was also chosen as the grandmother's bedroom because it faces the courtyard, allowing natural light to enter the room, which the grandmother values. Besides, the grandmother usually fries strong-smelling foods like fish in the courtyard. The house's owners also divided the first-floor area into two sections by adding a door to each section, creating an apartment separate from the other (Figure 11). This is because one of the two sections is inhabited by the spouses and their children, while the other is being prepared for the uncle who is planning to marry and settle there.

4.2.3.3 Interests

One of the things that homeowners are interested in is connectivity with nature and space ventilation. For this reason, when they built the living room and bathroom, they were determined to leave a space from the courtyard for ventilation, as explained by the interviewed householder. The grandmother also values the courtyard because she is passionate about home gardening. Besides, homeowners are also interested in family gatherings, which take place every weekend, especially since the house is considered "the grandmother's house, where the children and grandchildren gather," as described by the interviewed householder. They also prefer practical home solutions that are both affordable and long-lasting, whether for materials, furniture, or finishes. They have no interest in the aesthetic aspect of the design as they think that selecting practical solutions is more crucial, especially in the living room, where they perform most of the activities. During the interview, the householder also confirmed, "The modifications are based on the needs and priorities of the family." Privacy is at the top of their priorities, especially when men attend family gatherings and visits. So, the householder stated they would prefer an external door for the guest room.

FIGURE 11
The first-floor apartments after separation—Case study 3.

4.2.3.4 Opinions

The house's residents are pleased with all the modifications they have made because it meets their needs and provides leisure and comfort. According to the interviewed householder, "the space does not allow for more modifications, as any modification affects other spaces." However, the homeowners intend to use a portion of the garage space in the future to construct a toilet for the guest room that will be used by male guests, particularly during visits and family gatherings. They also plan to widen the front internal entrance lobby of the house and build a maid's room with a laundry room on the roof. The householder further emphasized the importance of incorporating natural lighting in all interior spaces of future housing units and increasing the size of the bedrooms and living rooms. The interviewee also believes that housing units should include a separate guest room with a toilet because "most Bahraini families require privacy while hosting guests, particularly non-relatives."

5 Discussion

The research aimed to explore the issues leading to residents' modifications in Bahraini subsidized housing through two phases. The first phase focused on the issues related to residents' common behaviors concerning the process of modifications through interviewing experts. Those are associated with three categories: Residents' common modifications, motivations, and mistakes. Regarding the common modifications, findings showed that residents desire specific preferences and new trends in housing design before inhabitation. Those preferences are related to different themes, including particular space arrangements and sizes, materials and design techniques, and housing components, both internally and externally. The analysis demonstrated that these themes lean toward simple modern designs. This supports the claim of Taki and Alsheglawi (2022) that Bahrain is heading toward modern designs, which most residents prefer. This is evident in the spacious spaces that most residents prefer, as interviews revealed that space expansion is the most common modification among Bahraini subsidized housing residents. Besides, the interviews indicated that space expansion mostly appears in living rooms and can be achieved through various methods, such as utilizing kitchen space. This was also confirmed by Saraiva, Serra and Furtado (2019), who stated that expanding the living room is frequently accomplished by utilizing the kitchen space. As a result, most residents add an external kitchen, which is another common modification, as the findings indicated. Salman (2016) also highlighted this, indicating that modern residences must have exterior kitchens to avoid strong odors produced by Bahraini cuisines. Additionally, expanding bedrooms is one of the modifications that residents constantly make to accommodate additional functions. Moreover, residents' preference for modern styles is also evident in their choices for sustainable modern-style materials and expansive glazed facades.

Regarding the common motivations, findings revealed that there are constant motivations behind the modifications represented in the three pillars of sustainability, particularly the sociocultural pillar. This reflects how strongly the Bahraini residents clung to their customs, traditions, culture, and values. This was evident in residents' concern for privacy, hospitality, and family gatherings. This was also highlighted and discussed by other studies (Alkhenaizi, 2018; Saraiva et al., 2019; Obeidat et al., 2022). Regarding the common mistakes, findings indicated that most residents commit widespread mistakes before and during the modification process. These mistakes cause damages that exacerbate the modification process and make it more complicated. This was also noted by Abdellatif and Othman, (2006), who explained some of those mistakes and their associated obstacles. Therefore, to implement the modifications accurately and effectively, selecting experienced contractors in addition to qualified design offices is crucial before beginning the modification process. This will help clients understand building codes and violations, as well as the dangers of working alone without the assistance of specialists. Therefore, knowing these mistakes helps avoid them in future projects and reduces the modifications (Chukwuma-Uchegbu and Aliero, 2022).

The findings of the second phase demonstrate that differences in residents' behaviors in subsidized housing related to their distinct lifestyles are strongly associated with the post-occupancy stage. In other words, many modifications are based on the lifestyle dimensions such as Demographics, Activities, Interests, and Opinions. For example, as demonstrated in the first case study, some residents may make specific modifications to meet the needs of an elderly family member. Some also intend to make substantial changes because their accommodation period was longer and revealed some issues with the modifications they made before occupancy, such as the fact that the modifications are not suitable for them, as evident in the second case study.

Furthermore, residents modify their dwellings to cater to their activities, which differ from one family to another because, as revealed by interviews with householders, residents' activities are closely related to their working and leisure time, visitors, and family gatherings. For instance, in the first case study, the homeowners concentrated on having a private space to practice their activities and hobbies, which was represented by the sitting area in the bedroom and the courtyard; in the second case study, the focus was on the kitchen because the housewife cooks frequently; and in the third case study, the homeowners concentrated on the living room because the house is considered the family home, where family gatherings take place regularly. Moreover, in all three cases, residents modified their housing units to accommodate their various interests. In the first case study, residents were most interested in luxuries, aesthetics, and courtyard design; in the second, homeowners were interested in spacious spaces and contemporary style; and in the third, residents were most concerned with privacy and cost savings.

In addition, the interviewed householders reaffirmed their intention to make modifications in the future, either because they realized one of the changes they had made was inappropriate or to accommodate new circumstances and future events, such as the marriage of one of the family members, or creating space for recent activity. This is consistent with the argument of Jensen (2009), who indicates that lifestyle evolves over time. Residents also demonstrated the significance of personalization in design by enabling them to customize their surroundings to suit their preferences and reflect their personalities. This was also emphasized and discussed by (Tipple, 1999; Marcus, 2006).

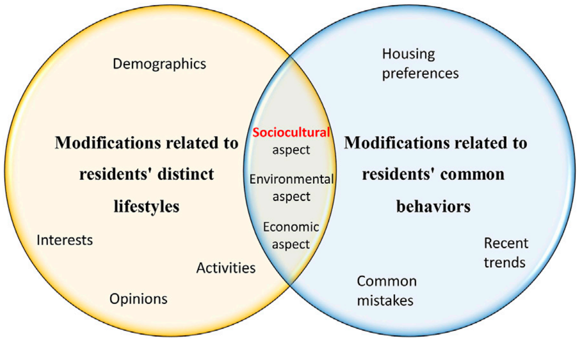

FIGURE 12
Sustainability aspects as motivational factors for residents' modifications.

This implies that many of the modifications made by residents are related to the lifestyles of families, as clarified by Aduwo, Ibem and Opoko (2013). These modifications vary because each family employs lifestyle dimensions based on priorities, resulting in different design patterns, as illustrated in Figures 3, 6, 9. In other words, this confirms and demonstrates the relationship between lifestyle and residents' various modifications, which was also indicated by Mirmoghtadaee (2009). Furthermore, the design patterns analysis revealed that the various lifestyle modifications are concentrated in specific zones. This is evident in the three cases through the different design solutions and future plans for the guest rooms, courtyards, and interior divisions for the extended bedrooms. Accordingly, providing flexibility in these spaces is recommended, as it will allow for the various modifications that residents may make over time (Aryani and Jen-tu, 2021; Obeidat et al., 2022). Simultaneously, it was demonstrated that similar modifications were implemented in the case studies, such as expanding living rooms and allocating space for the dining table, extending bedrooms, and using oversized windows and glazed sliding doors overlooking the courtyard. Experts have also identified these modifications as among the most common in subsidized housing units, indicating their importance to residents. Besides, residents have a common desire for sustainability aspects; despite the differences in residents' interests, they revolve around the three pillars of sustainability, particularly the socio-cultural aspect. This is consistent with experts' responses about the common motivations behind residents' modifications, implying that these aspects are considered motivators for residents to make general or specific modifications (Figure 12).

This is mainly prominent in the courtyard space in the three case studies. As shown in the patterns of residents' modifications, all homeowners used the courtyard space to expand their living rooms. Simultaneously, a portion of the courtyard was left with a different size in each case based on the homeowners' differing interests and priorities. According to the interviewed householders, they either need the courtyard to serve as a natural aesthetic view of the interior and a source of natural lighting and ventilation or to utilize its space for various activities. This emphasizes the importance of the courtyard for Bahraini residents. In agreement with this perspective, Lafi and Al-khalifa (2022) stated that the courtyard has considerable value for Bahraini residents because of its cultural, social, and environmental significance and its role in contributing to the privacy and sustainability of the house. This was further confirmed during the first phase of the research by interviewee #3, who pointed out that the presence of a courtyard in Bahraini residences is essential regardless of its size.

Therefore, after comparing and contrasting the behaviors of residents in Bahrain's subsidized housing during the two phases, it was found that the issues that lead to residents' modifications can be classified as follows:

- General issues represent the similarities of residents' behaviors in subsidized housing and are usually associated with the prior-occupancy stage. These issues affect the majority of residents, and they include the following:
    - Residents' preference for simple modern designs with openness and spacious interiors. This was abundantly clear through the common modifications that most residents make, such as extending living rooms and bedrooms, using trendy modern materials and techniques, and installing large windows and glazed sliding doors overlooking the courtyard.
    - Residents' desire for sustainable housing units that consider social, cultural, economic, and environmental aspects—with the sociocultural part having the most significant influence on this process because it is affiliated with critical factors such as privacy, hospitality, and the aesthetics and distinction of houses—means that residents' modifications are a complex process that necessitates a thorough investigation and comprehension of all of these aspects.
    - Damages caused by residents' common mistakes during the modification process, such as ignoring the consultation of the engineering office, hiring inexperienced workers, and being influenced by designs that do not meet their needs.
- Specific issues represent differences in the behaviors of subsidized housing residents and are usually associated with the post-occupancy stage. These issues relate to families' distinct lifestyles, as demonstrated by the different modifications made or to be made to the guest room, courtyard, and interior divisions of the extended bedroom. They include the following:
    - Residents' need to modify the house based on demographic factors, including the number and ages of family members, marital status, and occupation period.
    - Residents' need to modify the house based on their activities, which include their routines, habits, hobbies, and time use. So, it is linked to the functions performed by residents. Thus, the modifications associated with this dimension are typically related to the space size and arrangement.
    - Residents' need to modify the house based on their interests related to intangible factors, such as their desire for a particular style. It also includes residents' adherence to cultural norms and religious values, such as family gatherings and privacy, as well as their concern for natural resources, budget, and quality.

    - Residents' need to modify the house based on their opinions and perceptions. This includes their satisfaction with the current design and modifications, future plans, and perspectives on the essential housing requirements.

So, this fills gaps in the literature and answers the research question, which states: what are the issues that lead to residents' modifications in Bahraini subsidized housing units?

6 Conclusion

The process of residents' modifications in subsidized housing results from residents' behaviors associated with a combination of shared factors and distinctive lifestyles. This study has examined two dimensions: similarities and differences in residents' behaviors in Bahraini subsidized housing. The findings indicate that most Bahraini residents prefer simple, modern designs with spaciousness, openness to outdoor spaces, and modern materials and techniques. Results also highlight the importance of sustainable housing units that incorporate all three aspects of sustainability, particularly the socio-cultural. They have also revealed the critical role of experts in this process in minimizing these modifications and avoiding violations when hiring them from the beginning.

Moreover, results show that lifestyle has a strong relationship with these modifications. Therefore, it's crucial to consider the common behaviors of residents in subsidized housing when designing future housing projects. Simultaneously, housing units must be flexible and adaptable to accommodate the evolving lifestyles of families and allow for modifications at any time. This will, in turn, contribute to reducing and streamlining the process of modifications.

This study also confirms the significance of studying the two directions related to residents' modifications in subsidized housing: similarities in the prior-occupancy stage and differences in the post-occupancy stage. This is because most previous studies concentrated solely on the post-occupancy stage, although residents usually begin making modifications during the pre-occupancy. Future research should therefore focus on these two directions investigated in the two phases of this study: the first phase was general, related to similar and repetitive behaviors of most people. In contrast, the second phase was more specific and linked to the behaviors of individual families and their different lifestyles. So, studying both phases is essential to determining the issues leading to residents' modifications in subsidized housing. Thus, both of them were required to answer the research question comprehensively. This study provides a comprehensive conceptual framework for studying the two directions. It lays the groundwork for future research addressing the same issue in different regions in Bahrain, the Gulf countries, and worldwide. Therefore, the research proposes using the same two-phased methodology to study the same issue in other housing projects locally or regionally. Despite its antiquity, modifications are ongoing and must be explored from time to time in different regions. This study focused on the East Hidd project, so further research should focus on other housing projects in Bahrain to explore other issues related to this phenomenon.

Data availability statement

The datasets presented in this article are not readily available because raw data is restricted for access to keep the privacy of identifiable matters. Requests to access the datasets should be directed to maywlafi@gmail.com.

Ethics statement

The studies involving human participants were reviewed and approved by the Research and Scientific Publications Committee. The patients/participants provided their written informed consent to participate in this study.

Author contributions

ML, HA, and AJ contributed to the conception and design of the study. ML wrote the literature review and conceptual framework, collected the data through interviews and case studies, analyzed the data, and wrote the discussion and conclusion. The scope of the literature review, criteria of case study selection, guidelines for interview questions, and method of interpretation of collected data were suggested and finalized by HA and AJ. The draft manuscript was prepared by ML and reviewed and edited by HA and AJ. The research was fully supervised from inception till finalization by HA. All authors contributed to the article revision and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Design and delivery of national housing in the UAE: an alternative approach

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The provision of national housing to citizens in the United Arab Emirates (UAE) is considered a crucial topic. Over the past four decades, the process of developing national housing has emerged into multiple housing programs and schemes, all with the same aim of offering affordable and high-quality housing to citizens, in addition to meeting the needs of local families regarding spatial configurations while maintaining cultural values. However, despite all these efforts, the question has always remained: are the offered housing practices suited for family needs, socioeconomic trends, and environmental challenges? This study aims to offer an alternative approach for the design and delivery of national housing practices in the UAE. The proposed process is structured based on the following ethos: first, a conceptual approach for design flexibility toward offering customization while maintaining contextual and cultural qualities for inhabitants; second, a computational design strategy for facade optimization that illustrates the significance of incorporating environmentally conscious design strategies in response to local climatic conditions toward enhancing overall building performance; and third, a hybrid production model that relies on a prefabricated building approach that combines precast concrete systems with 3D printing technology. The efforts described in this article represent a significant phase of an ongoing research endeavor that explores how technological capacities could help rethink national housing in the UAE.

KEYWORDS

housing, design flexibility, customization, computational design, 3D printing

1 Introduction

Back in the late 1960s, when Sheikh Zayed Al Nahyan, the ruler of Abu Dhabi, came into power, he called for a new national housing initiative that aimed at building a nation, settling the nomadic Bedouin, and increasing the emirate's population. At that time, he engaged international architects and consultants to design public housing. Such an initiative resulted in multiple critical attempts that explored layout possibilities, spatial configurations, and construction techniques toward devising a viable solution for national housing. Later in the early 1970s, with the federation of the United Arab Emirates (UAE), the call expanded, resulting in a remarkable interest in exploring the potential of using modular prefabricated concrete components due to their capacity to cut construction time, thus speeding up the building process (Damluji, 2006).

During the last few decades, along with remarkable urban growth and the development of modern infrastructure across cities in the UAE, the call to deliver national housing has expanded to a wider range of its citizens. Public housing projects are being developed in every city as government bodies have invested heavily in housing developments through collaborations with the private sector in order to diversify the process and the end product, and thus deliver high-quality housing to the public (Agrawal et al., 2020).

In recent years, housing communities have been developed to meet the high demand for Emirati families, thus resulting in projects that are large in scale and complex in process. In order to orchestrate the procedures, the local housing authority has devised a series of design and construction guidelines that are set to maintain the sociocultural identity of citizens while providing housing typologies that are shaped in response to local demographics (Abu Dhabi Housing Authority, 2016). For instance, many of the recently completed projects have relied on precast concrete systems either entirely or partially, given the method's practical and economic vitality. Nevertheless, an analysis of some of these projects that have been recently completed in the emirate of Abu Dhabi has revealed a series of concerns regarding spatial configuration, design flexibility, and environmental performance. Additionally, there is an inadequacy in endorsing inhabitants' individual preferences within the design (Elkaftangui and Eid Mohamed, 2018). While housing authorities have been committed to delivering high-quality housing, we argue in this work that many of the previously mentioned concerns are due to relying on design and delivery practices that are flexible enough to accommodate possible variations in inhabitants' individualities and in being responsive to contextual characteristics. As a result, despite all these efforts, we sought to question in this work how emergent design and fabrication technologies can offer an alternative to the current housing practices. The focus is on the potential to overcome a series of challenges such as the capacity to respond to local citizens' needs, utilized construction methods, changing socioeconomic trends, and contextual specificities, through an approach of rethinking the design and delivery process.

In order to respond to the formerly mentioned questions, we propose in this work a comprehensive approach for the design and delivery of national housing in the UAE, one that relies on three ethos. First, a design flexibility scheme that could allow for various levels of customization, from spatial configuration to room blocks modification. Second, a computational design process for optimizing a self-shading facade system that aims to leverage the building's environmental performance. Finally, a hybrid production model that maintains a prominent off-site construction practice by combining precast concrete systems, integrated utility pods, and large-format 3D printing.

The proposed approach emerges in response to exploring the challenges of current practices while realizing the potential of emergent trends and technologies in the building industry. Thus, this work is structured as follows. The first section offers the background on a series of topics that aims to lay the base for the proposed approach. This includes the evolution and development of Emirati housing, various design drivers, and current housing practices in design and construction. The section leads to the identification of what we believe are the challenges being faced in current practices and the potential topics that can be explored toward devising an approach for the design and delivery of national housing. The second section outlines the proposed schemes and various strategies that we have sought to integrate, such as modularity and design flexibility, facade optimization, and prefabricated building systems. Finally, the last section gives the conclusion and future work.

The work presented in this article represents a critical phase of an ongoing research endeavor that aims to rethink the role that design and fabrication technology can play in changing national housing practices in the UAE. The goal is to develop a digitally driven workflow that relies on a series of technological procedures toward an affordable, customizable, and environmentally conscious housing system. It is worth mentioning that affordability in such a case refers to the housing authority's financial capacity to fulfill citizens' demand for housing. The focus is on devising a protocol that could potentially leverage current design and production practices while maintaining contextual attributes that are shaped by local environmental challenges, coupled with citizens' sociocultural requirements.

2 The case of UAE national housing

2.1 Background

Housing in the UAE's capital, Abu Dhabi, started off as residential clusters split tribally into quarters called *hara* or *fareej* connected by internal walkways called *sikka* (Ahmed, 2012; Boussaa, 2006; Hassan, 1972; Bani Hashim, 2016; Rashid et al., 2022). The walkways connected each quarter to distinct community facilities, such as mosques, *barahaat*, or public spaces (Ahmed, 2012; Bani Hashim, 2016). Most buildings were mainly constructed from a semi-permanent palm frond structure called *arish*, along with a few elite houses constructed from coral, mud-brick, or clay. A few of the latter contained an upper floor and a wind tower for cooling purposes (Heard-Bey, 1982; Kay and Zandi, 1991; Al Fahim, 1995; Heard-Bey, 2001; Hawker, 2008; Bani Hashim, 2016; Elsheshtawy, 2019; Rasid et al., 2022). Extended families lived in the typical household, where a rectangular fence surrounded the house and its courtyard, and each *fareej* faced north for protection from direct sunlight and attracting north wind, which provided an additional cooling effect (Bani Hashim, 2016).

On the micro-level, none of the rooms or courtyards had windows at eye level to the outside. This together with the curtain walls that were placed opposite to the rear door enhanced visual privacy (Heard Bey, 2001; Bani Hashim, 2016; Elsheshtawy, 2019). Structural frames and roof beams were composed of palm trunks. The palm branches were tied together with fiber ropes that surrounded the foot of the tree trunk, which allowed for large solid mats to be made, thus forming the walls of the house (Bani Hashim, 2016). The gaps in the walls allowed summer wind to enter the house and served as a natural ventilation. In the winter, however, several layers were added to the walls for warming effects. Furthermore, palm ponds were woven into several layers of thin mats to form the roof. Floors were made of sand, sometimes covered in the same thin palm pond mats (Heard-Bey, 2001; Bani Hashim, 2016).

With the discovery of oil, and the British withdrawal from the region, in the 1960s, foreign consultants were hired to generate master plans for the city to design new residential neighborhoods, to

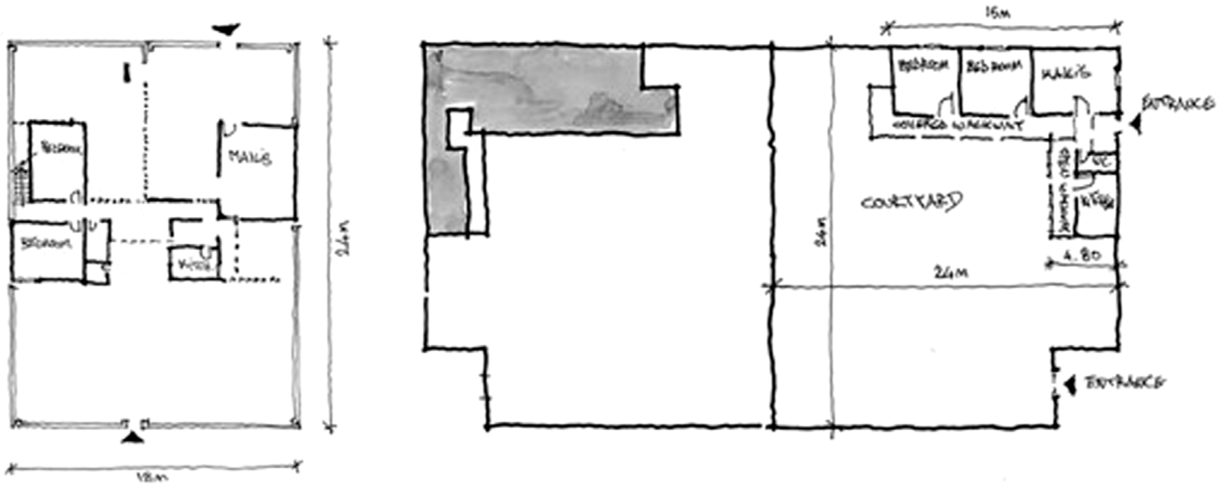

FIGURE 1
Image from the late 1960s in Abu Dhabi showing the final stages of constructing a *Sha'bi* house. Source: ADCO; Elsheshtawy (2019).

accommodate local and expatriate residents. ARABICON was hired, and national housing initiatives started to materialize, urbanize, and settle nomadic Bedouin families and tribes, who contributed to building the nation and boosting growth and social development, resulting in initiatives like the *Bayt Sha'bi* (the national house), where standard housing units made of concrete and equipped with electricity, sewage disposal systems, and running water were designed (Heard-Bey, 1982; Damlūji, 2006; Dempsey, 2014; El-Aswad, 2014; Sadik and Snavely, 2014; Bani Hashem, 2016; Bani Hashim, 2018; Rashid et al., 2022). Later, all housing and planning activities as well as the ARABICON staff were moved to Abu Dhabi City Municipality (ADM) (Bani Hashim, 2016; Kyriazis et al., 2017; Rashid et al., 2022), where the Egyptian planner Abdul Rahman Makhlouf led the planning process of modern Abu Dhabi in 1968 (Rashid et al., 2022; Bani Hashim, 2016; Elsheshtawy, 2019). Following this, national housing continued under Makhlouf's role as Abu Dhabi's Chief Planner, with traces of influence from the Japanese planner Katsuhiko Takahashi (Rashid et al., 2022; Bani Hashim, 2016). Eventually in 1988, WS Atkins & Partners Overseas (Atkins) was commissioned to generate a comprehensive development plan for Abu Dhabi and its environs. They worked on it for 2 years, and the plan was released in 1990 (Bani Hashim, 2016).

The tradition of giving every Abu Dhabian plots of land for residential, commercial, industrial, and agricultural use had already been in practice (Bani Hashim, 2016). They were now known as "*social housing*" programs, denoting the strong correlation and effect of architecture on social life (Rashin et al., 2022). Furthermore, the granting of social housing was restricted to lower income residents, and even though priority was given to households composed of 6+ family members, they were granted under the condition that the head of the household did not already possess a house or land (Bani Hashim, 2016).

Initially, houses of the Social Housing Program were built on approximately 400-square-meter plots (Al-Mansoori, 1997; Wimsatt, 2010; Leech, 2016; Rashid et al., 2022). As the building occupied only 40% of the plot, the resultant area of the house did not exceed 200 square meters (Elsheshtawy, 2019), with a 3-m-high fence (Al-Mansoori, 1997; Wimsatt, 2010; Leech, 2016; Rashid et al., 2022). The interior of the house consisted of two bedrooms, a living room—*Majlis*, a kitchen, a bathroom, a shower, and a courtyard (Elsheshtawy, 2019; Rashid et al., 2022). Furthermore, as a means of space optimization, residents used the flat roof as an additional sleeping space (Rashid et al., 2022; Elsheshtawy, 2019). Figure 1 shows a reconstructed floor plan of a *Sha'bi* house. Social living and communication were emphasized via the addition of open green spaces and courts between the dwellings, which also increased the sense of privacy among each group of houses (Rashid et al., 2022).

By the 1970s, national houses (also then known as low-cost houses) were mass-produced. This resulted in communities that lacked a clear structure, identity, and adequate community facilities (AHDA, 2014; Bani Hashim, 2016). This is evident by the replacement of traditional materials with prefabricated concrete structures, which retained heat even during the night, resulting in a dependency on air conditioning and rendering the houses environmentally unsustainable (Architectural Review, 1977; Bani Hashim, 2016; Rashid et al., 2022). Furthermore, houses were also socially unsustainable as they failed to respond to cultural needs and values, which resulted in external and internal modifications and additions to the housing units (Bani Hashim, 2016; Rashid et al., 2022). This initiated a need to encourage more environmentally sustainable houses (Al-Mansoori, 1997; Rashid et al., 2022) and increase the plot sizes over the next 20 years to reach approximately 45 m × 60 m (Abu Dhabi Housing Authority, 2014; Bani Hashim, 2016).

Between the years 1971 and 1976, over 40,000 residential housing units were built, and by 1980, more than 20,000 residents were on the waiting list, indicating the popularity of these houses (Elsheshatwy, 2019). However, as pressing needs for mass production increased, despite multiple modifications, the national housing program inside the island of Abu Dhabi stopped in the mid-to-late 1970s due to the size of families outgrowing the size of a standard national house (Bani Hashim, 2016; Rashid et al., 2022). Instead, the national houses were marked for demolition when the new development plan for the capital was initiated (Al Ittihad, 1978; Bani Hashim, 2016; Rashid et al., 2022). On the other hand, by 1985, most of the national housing projects focused on the Al Ain city and its rural areas (Atkins and Overseas, 1990; Bani Hashim, 2016). Since 1990, heritage and regeneration projects have been going through constant refinement to adapt to the rapid cultural changes caused by globalization, tourism, and interaction with expats from around the world (Rashid, et al., 2022; Hawker, 2008; Heard-Bey, 1982).

Today, stand-alone, two-story villas, marked as "Houses for the Nation," form the dominant form of national housing in the UAE. These are equipped with hot water, green-star-rated air conditioning, and fiber optic networks (Rashid et al., 2022). However, the problems with their environmentally unsustainable features remain.

2.2 Cultural and environmental drivers

In the pre-oil era (before the 1950s), the Emirati culture constituted a tribal system. At which time, tribal affiliations had influenced the building blocks of the Emirati cultural fabric (Heard-Bey, 1982; Thesiger, 1995; Trench, 1996; Rashid et al., 2022; Al Abed and Hellyer, 2001) Emiratis made their living from different professions, which included fishing, trading, pearling, and cultivating dates (Rashid et al., 2022). These professions played a crucial role in shaping the Emirati culture, even after the discovery of oil, and still do to the present day. This has resulted in the formation of the neighborhood—*Fareej*, which is made up of urban space in which houses are located.

In the Emirati culture, houses are seen as a sanctuary, that is, to be respected by people—Haram (El-Aswad, 1996; El-Awaad, 2014), which results in significant cultural value to the house as a structure (El-Aswad, 1996) and triggers a need to address the culture as a driving force that leads to the designing of residential units in the UAE. One of the main concerns when designing houses is gender-related activities. For instance, the need for two reception halls—*majlis* or *maylis*—in each unit is crucial to the Emiratis to serve each gender separately (El-Aswad, 1996). Furthermore, the tribal structure is still strong in the formation of the social fabric. This has resulted in four main categories of houses that have been identified by El-Aswad (1996) as 1) the grand palaces, which belong to ruler families, sheikhs; 2) large villas that belong to wealthy families; 3) modern, western buildings that are composed of individual apartments merged together; and 4) traditional or folk houses—*Bayt Sha'bi* (El-Aswad, 2016).

Typically, a folk house is a horizontal, single unit that has a simple, single-story layout consisting of basic functions, such as courtyard, guest reception or sitting room—*majlis*, bedrooms, storage areas, a cooking area or kitchen, a bathroom, and a seating area overlooking the courtyard—*Iiwan*. These houses are often surrounded by 2- to 3-m-high outer fences—*Jadar* and are separated from each other with a minimum of 1-m-wide vacant space (El-Aswad, 2016).

Nonetheless, the folk house has always been subject to modifications due to extended families and the ever-changing needs of its residents. Some of these modifications have been approved by the municipality, such as the replacement of exterior wooden gates with decorated steel or metal doors or the further addition of spaces to accommodate more functions (an additional bedroom, a majlis, or a garage), and they have remained connected to community acceptance and social, economic, and functional needs of the residents. Regardless of how drastic some modifications may be, the folk houses remain inward-looking, with all the original and added functions arranged around the central courtyard, emphasizing the need for privacy in the Emirati culture (El-Aswad, 1996).

The need for privacy also affects houses from the outside, where trees—more particularly, palm trees—are perceived as a symbol that offers a sense of privacy and security, along with enhancing the houses' esthetics as well as the environment. The units are often separated from their neighboring houses by a minimum of 1-m-wide empty spaces (El-Aswad, 1996; Rashid et al., 2022). Some are also surrounded by a garden. Despite the presence of garages in most houses, it is common to see cars parked in the front. Nonetheless, the entrances are perceived as an important way of protection. As a result, house entrances are not shared with anyone outside the family domain, that is, living in apartment buildings or buildings with shared entrances is not historically common in the Emirati culture. Consequently, each individual unit has two entrances: the first leading to the *majlis*—men's reception and sitting hall, while the other entrance leads to the rest of the private spaces of the house. The women's *majlis* is typically connected to the interior of the house, more specifically, adjacent to the house's back entrance (Boussaa, 2006; Coles and Jackson, 2007; El-Aswad, 2014; Rashid et al., 2022). The men's *majlis*, on the other hand, is often larger and connects the interior to the exterior world, making it a symbol of hospitality, generosity, and sociability. This renders the men's *majlis* a crucial part of the Emirati house due to its connection to the exterior and interior sides of the house (El-Aswad, 1996). The importance of the men's *majlis* calls for special attention to ornamentation and decorations on its openings (Rashid et al., 2022; Kay and Zandi, 1991; Remali et al., 2016).

The folk house's courtyard, on the other hand, represents the core and intimate side of the house, where residents, especially women, get to enjoy nature in privacy. Some women use the courtyard as an extension to the kitchen, allowing them to enjoy cooking in a natural setting while avoiding spreading unpleasant smells to the bedrooms and other spaces of the house. Children also benefit from the courtyard, as it serves as a safe outdoor playing area, away from the streets. Finally, the courtyard offers the entire family a comfortable space with natural ventilation in the UAE's hot climate (El-Aswad, 1996).

The *Iiwan* is another important component of the Emirati folk house. Having an open hall with a sitting area facing the courtyard, it is often decorated with geometric patterns. It is a roofed, centralized space between two rooms. Being open from one side, it benefits from an attractive view, making it a favored space for social interactions among family members (Kay and Zandi, 1991; El-Aswad, 1996; Hassan, 1972).

In addition to the functional aspect, attention to the little details and decorations have enhanced the esthetic appeal of the Emirati folk house. Folk decorations and paraphernalia symbolize the local culture. Doors, for instance, are painted with colors of the local folk style. Paraphernalia and decorations are inspired by nature, such as indigenous plants, flowers, and birds. The falcon is a distinctively important bird that is commonly used due to its significance in the Emirati culture (El-Aswad, 1996).

The outside area of the houses is not exempt from those decorations. Arches, crescents, stars, and domes are some elements that make up the exterior gates. Furthermore, facades are often decorated using local geometric patterns, which often include calligraphic religious phrases (El-Aswad, 1996).

Today, the influence of the Emirati culture on houses is clearly apparent in the typical house design and layout. A typical house of an Emirati still has its own entrance, at least one *majlis*, tall fences, and outside gardens. In short, the Emiratis' strong connection to their heritage implies that almost no changes can be made without a reference to their cultural heritage (El-Aswad, 2014; Elsheshtawy, 2019).

2.3 National housing practices

The public housing projects in the emirate of Abu Dhabi, UAE, which are the focus of this research, are governed by the Abu Dhabi Housing Authority (ADHA), which was established in 2012. The ADHA's goal has always been focused on delivering housing to citizens in Abu Dhabi, Al Ain, and the Western Region according to the highest standards [Abu Dhabi Housing Authority (ADHA), 2016]. Such a role has been materialized through collaborating with the private sector and establishing various initiatives and projects that have been aimed at facilitating the delivery of housing to citizens, thus speeding up the process.

As for initiatives, for instance, Bayti (2015) was launched in 2015 as a catalog of 58 housing prototypes designed by different architectural practices in the UAE. All typologies were preapproved for permitting and constructing, with the aim of speeding up the process and minimizing the risks in design, development, and construction. Housing prototypes were also designed to match standardized lot sizes within future developments. Ranging from four to possibly eight-bedroom houses (400–1,000 m^2), the catalog catered to various family needs regarding spaces, style, and amenities. Due to challenges in managing the process, in addition to dissatisfaction with the offered housing prototypes, the initiative model was set as a secondary option, and the focus transformed into a wider collaboration with the private sector toward comprehensive housing developments.

More recently, another initiative has been proposed—Teyaseer, an Arabic word meaning facilitation, and established in Abu Dhabi in order to act as a liaison between Emiratis registered in the housing program and different developers working on national housing projects. It is an optional free service that national housing loan recipients who are not very experienced with the process of building a house can use to overcome any difficulties that they might face during the process of building their homes. On their website, Teyaseer offers a catalog of housing typologies that vary in size from four to seven bedrooms (400–700 m^2) and style (modern to traditional) (Teyaseer, 2022).

Pertaining to projects, the Al Falah Community was developed in Abu Dhabi in 2015 that consists of five "villages" comprising 4,857 villas, in addition to a wide range of community amenities. The development, which is considered to be one of the largest housing developments in the capital, aimed to provide a sustainable neighborhood that serves modern requirements and lifestyles while preserving and promoting the traditional Emirati identity and preferred style of living [Abu Dhabi Housing Authority (ADHA), 2016]. The project was planned with five villages, each designed around the notion of open spaces and communal amenities and comprising a series of housing typologies and villas that had distinctive layouts and facade styles. Figure 2 shows an aerial view of the project.

2.3.1 Precast concrete industry in UAE

Concrete is one of the most usable materials in construction worldwide, and specifically in the MENA (Middle East and North Africa) region. It is considered a cheap composite due to the low cost of raw materials. Additionally, it is a strong material in compression, durable, resistant, and versatile. One of the most common applications in concrete construction is precast concrete, a production model that operates by building up offsite molds and formwork for each specific project. It is used for walls, floors, and structural elements. Once complete, these components are delivered to the construction site and then assembled by using cranes to form the building (Bachmann et al., 2012).

Over the past decade, there has been a growing interest in the use of precast concrete elements due to their superior quality, durability, ability to compress project schedules, reduced site disruptions, and improved sustainability (Sayed, et al., 2007). Villanueva (2020) argued that the precast concrete market in the UAE is anticipated to grow at a rate of 4.4% between 2018 and 2024, with structural products accounting for approximately 50% of the overall construction market value in 2020.

In recent years, the precast concrete systems have been employed extensively to realize many of the national housing projects in the UAE. In such cases, houses are built using structural and non-structural wall panels in an engineer to order fashion, in addition to hollow core slabs, beams, and stairs. Precast concrete is believed to be a faster, more durable, and sustainable technique for construction, especially for residential structures, when compared to conventional methods (Sayed et al., 2007). For example, the previously mentioned Al Falah Community project relied extensively on precast concrete systems. As a result, five villas were built per day, and labor costs were reduced by up to 25% when compared to conventional methods. Nevertheless, the project witnessed a remarkable volume of post-occupancy modification requests, directed primarily toward the spatial organization, fenestrations, and energy consumption–monitoring system. Due to the structural system employed, coupled with the design approach, implementing modifications has always been a challenge, which has led to, in some cases, dissatisfaction with the housing schemes (Elkaftangui and Eid Mohamed, 2018).

2.3.2 Reflection: challenges and opportunities

There are not many publications on the designing process of national housing in the UAE, given that it is a topic of practice rather than research. Furthermore, most of the work published has been focused on analyzing the existing strategies and projects. To mention a few, Agrawal et al. (2020) evaluated the effectiveness of housing programs in Ras Al Khaimah, one of the UAE's seven

FIGURE 2
Aerial view of the Al Falah project and facade of one of the housing units (source: Gulf Precast website, 2022).

emirates. Ahmed (2017) analyzed factors that contributed to sustainable community development and planning (Bande et al., 2019), and examined the relationship between spatial layouts of housing units, their orientations, and accordingly, the cooling loads of the housing units, while maintaining factors of local culture. Ahmed et al. (2022) also explored digital tools toward preoccupancy evaluation.

Based on exploring previously mentioned strategies and relevant challenges, observing recent housing practices and reviewing some of the research produced in various areas, we sought to question the possibility of proposing a new protocol for the design and delivery of housing prototypes. The proposed approach highlights a series of opportunities that stem from precedent efforts in housing designs that include, for instance, design flexibility and customization (Schneider and Till, 2005; Habraken, 1972; Duarte, 2001), facade and opening optimization (Caldas and Norford, 2002; Tuhus-Dubrow and Krarti, 2010; Kirimtat, et al., 2019), prefabricated building strategies (Kieran and Timberlake, 2004), and 3D concrete printing (Bos et al., 2016). We believe that such ideas offer a resilient medium to overcome current practices.

It is important to mention that the rationale of the presented research emerges based on two considerations: first, working closely with housing authorities, thus establishing a critical appraisal of implemented initiatives and offering housing catalogs, and second, examining one of the major housing projects delivered using precast concrete in order to understand various implications that limit flexibility.

3 Design and delivery scheme

The proposed design and delivery scheme stem from critically understanding the challenges that current national housing practices face. Nevertheless, it is important to mention that such a proposition does not seek to replace current practices but rather highlights the potential of applying a series of strategies that could overcome some of the challenges and thus offer an alternative. In that sense, the proposed scheme focuses on three main drivers: first, design for flexibility toward customization; second, optimization of facade openings toward better building performance; and third, utilization of prefabricated building systems based on precast concrete systems, combined with 3D printing. The following sections underline how we anticipate the integration of these drivers toward a comprehensive approach.

3.1 Design for flexibility

The study of national housing projects, specifically ones realized using precast concrete components, reveals the challenges in offering design flexibility and variations due to the pursued design approach, combined with the construction method. In that sense, one of our goals in this research is to offer a strategy for the design of housing prototypes that could allow for a certain level of flexibility and customization. As a preliminary scheme, we explore the notion of implementing a modular design approach. Modularity in design supports multiple configurations by using repetitive elements toward scaling and scope. This enables accommodating design variations on multiple levels, which is considered a core criterion in offering flexibility (Kieran and Timberlake, 2004). We propose devising an approach to spatial configurations, that is, based on a scalable modular grid system of 3.0 m × 3.0 m modules for generating floor layouts. In that sense, all of the interior blocks start with a minimum dimension of 3.0 m or its increments. This also informs exterior wall panels. For further flexibility, we incorporate half a module, 1.5 m, to allow for expanding spaces. The proposed architectural grid stems from design guidelines set by authorities for national housing developments in Abu Dhabi [Abu Dhabi Housing Authority (ADHA), 2016], which forms the basis for many of the spaces, according to their proportions.

Following various iterations for the spatial layout and in order to offer choices to homebuyers, we came up with three different variations for the typical plot: compact, atrium, and courtyard

FIGURE 3
Typical plans for one of the proposed housing prototypes, the "courtyard house," in addition to the structural proposal where load-bearing walls are marked in red.

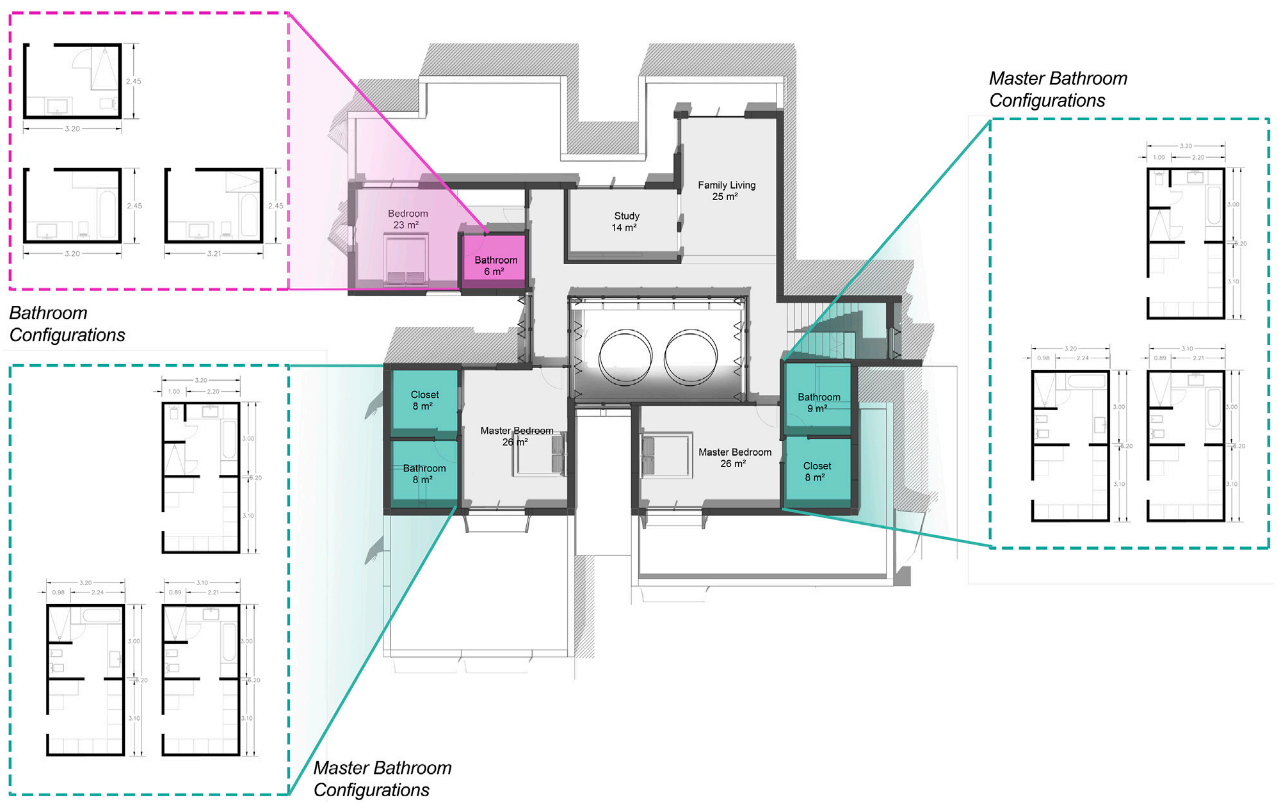

FIGURE 4
Micro-flexibility and customization in the upper floor of the "courtyard house" and exploring the possibility of various layout possibilities for the bathroom block.

houses; each one is a four-bedroom dwelling unit that can be expanded to seven. The proposed layouts follow typical design strategies for national housing in the UAE and incorporate all the required spaces while respecting cultural and social values. For instance, the separation between public male and female zones, considerations for aging in places in the form of future expansions, and provisions of adequate spaces for services. Nevertheless, the proposed layouts have been formalized around two notions of flexibility: macro and micro. On the one hand, macro-flexibility allows for spatial expansion as per the design brief that requires considering the notion of aging in place. In order to achieve the aimed flexibility, the structural system informed by the

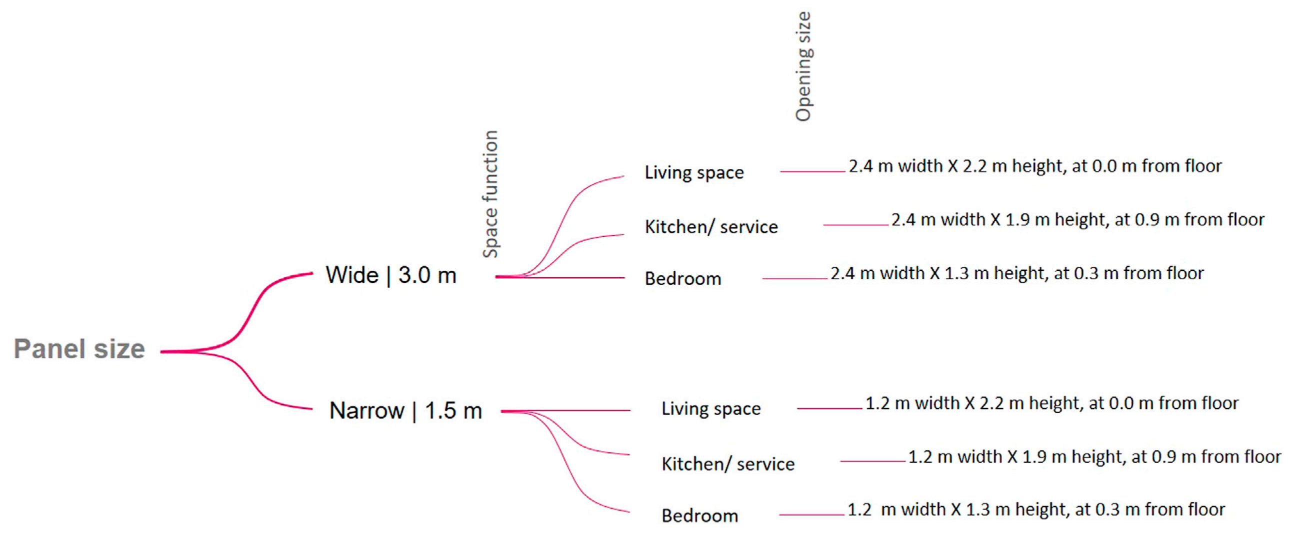

FIGURE 5
Classification of wall panels. Panels are designed based on a series of assumptions derived from examining residential design trends in the UAE, with a specific focus on opening size in relation to allocated function.

use of precast concrete components and following the proposed architectural grid is designed where only peripheral walls are allocated as load-bearing walls while the interior ones are set as lightweight partitions, as shown in Figure 3. Accordingly, homebuyers would be allowed the possibility to customize the spatial configurations of the housing units by moving, shifting, or removing some of the interior walls.

On the other hand, micro-flexibility allows for internal layout manipulation through the manipulation of utility spaces, kitchens, and bathrooms, thus offering room block modifications. These blocks have been initially designed and integrated within the three prototypes based on the notion of commonality. Commonality refers to the possibility of using a component both within the same product and between different products. The combination of modularity and commonality leads to a configurable product platform that can contribute to reducing costs (Tseng and Piller, 2003). Figure 4 represents customization possibilities for bathroom blocks.

3.2 Facade system

One of the major factors that has to be considered while designing buildings in the UAE is harsh conditions in the form of high heat and humidity during the summer. In order to cope with such conditions, buildings tend to rely extensively on active systems to achieve comfort within indoor spaces. However, these systems represent a significant portion of the construction cost and energy requirements, in addition to their environmental impact (Awadh, 2014). In order to cope with such a challenge, we propose a process for the design of a facade system that would contribute to the environmental performance of the housing units, thus becoming the first layer of protection against climatic conditions.

The facade system is composed of two typologies: insulated solid panels and window-hosting panels; both following the previously described modular strategy, with a basic panel that is 3.0 m wide and a sub-module that is 1.5 m wide. The purpose is to accommodate various possibilities for fenestrations as per spatial requirements, follow market standards, and leverage typology-based flexibility. Figure 5 demonstrates the classification of panel sizes according to the assigned spatial function.

While the solid panels follow industry standards regarding composition, the window-hosting panels integrate self-shading elements that are optimized for daylight through computational logic. We sought to employ a computational design logic based on an evolutionary generative algorithm toward devising unconventional solutions. Evolutionary algorithms are employed due to their capacity to simulate the processes of natural selection and reproduction, thus shaping the evolution of solutions in response to a problem (Bentley, 1999). In architecture, optimization applications through evolutionary computation have been explored since the late 1990s toward various types of design problems. To mention some of the early works: exploration of the matter of computers and assisting in the creative process (Gero, 1996), form finding (O'Reilly and Ramachandran, 1998), lighting and thermal performance optimization (Caldas and Norford, 2002), and opening size (Tuhus-Dubrow and Krarti, 2010). Commonly, when the case relates to building performance, the optimization model is combined with a simulation engine to ensure adequate solutions.

3.2.1 Optimization of window-hosting panels: developing panel taxonomy

Window-hosting panels are sought to play an important role in the environmental performance of the housing unit by being a potential source of heat gain. Accordingly, providing shade is

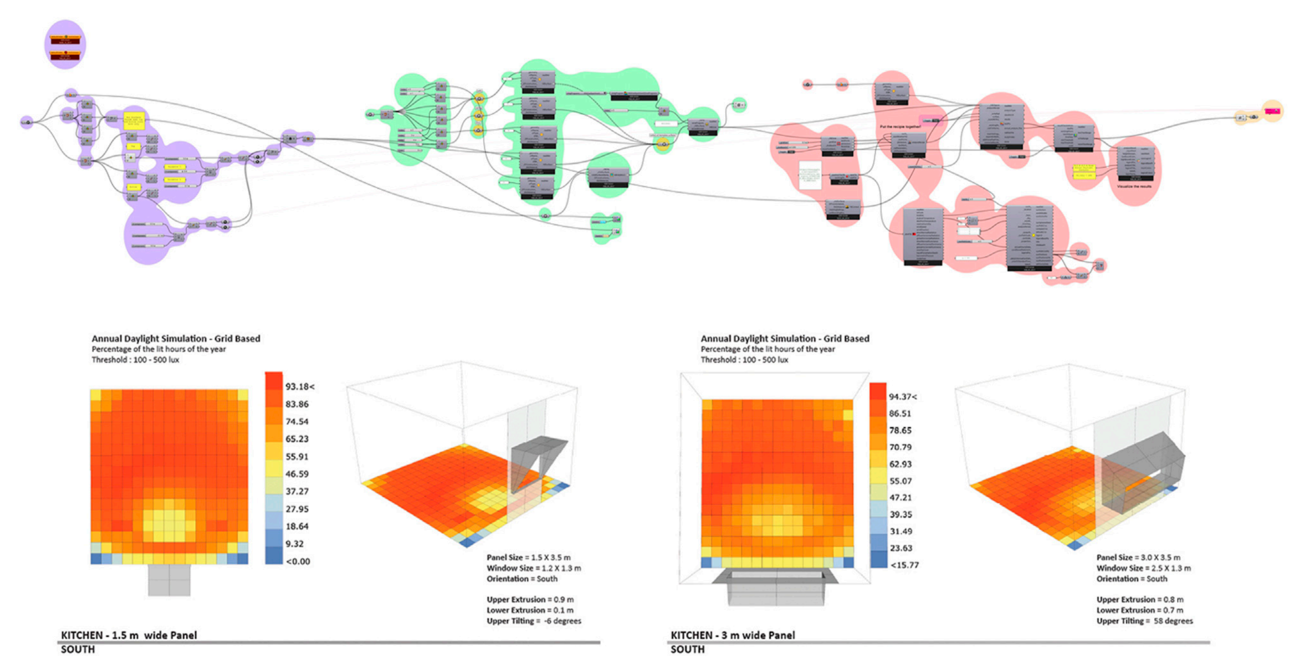

FIGURE 6
Above: the optimization process realized though combining a series of computation tools. *Below*: the outcome of optimizing a south-oriented 1.5-m-wide window-hosting panel when compared to a 3-m-wide panel. Color codes indicate the annual percentage of achieving optimal heat gain and lighting conditions for each grid square of the layout.

inevitable. The proposed self-shading element is integrated within the panel, thus taking advantage of the plasticity of concrete. As a starting point, the self-shading element is set within a predefined volume and controlled by a series of parameters in the form of vertices in the *x*, *y*, and *z* directions. The purpose is to allow for flexibility in performance optimization through manipulating parameters in response to orientation. Additionally, in order to control the generation process, a set of constraints related to opening guidelines in the UAE were involved, in addition to the modular grid.

The optimization process is initiated by devising a typical room model in the Rhinoceros (Rhino3D) software with one glazed opening, hosting a non-uniformly extruded virtual shading element. While the shading element is set to be computed as a dynamic component, it follows the perimeter of the fenestration at this stage. This generic configuration is then fed into the Grasshopper, the visual programming platform, where the optimization process occurs. The Grasshopper definition interprets the basic geometry and identifies it within the digital model's bounding elements: walls, floors, ceilings, and glazing zones. It also enables the input of orientation as a predefined parameter: south, southeast, east, southwest, or west. Then, the shading element parameters are established. Being a core feature in the Grasshopper, the process is characterized by building up associative relationships with a clear set of parameters and a range for their values. This dynamic setup is then optimized by manipulating extrusion parameters in the *x*, *y*, and *z* directions for the sake of optimizing the configuration of the shading element to the fittest according to orientation, using carefully calculated fitness criteria between annual illumination levels and solargain levels to achieve the most efficient performance.

Running the optimization requires the use of Grasshopper plugins and components, each performing a very specific task within the whole process. Galapagos, the evolutionary solver, is utilized to orchestrate the process of searching within a pool of solution space for the fittest solution with regard to the shading system parameters in the *x*, *y*, and *z* directions, thus resulting in a specific configuration. To ensure adequate performance, the process is combined with Honeybee, Ladybug, EnergyPlus, Radiance, DaySim, and OpenStudio, a series of necessary components in the Grasshopper for building energy and daylight simulations. These components act as normalizing media for the form-finding process, hence ensuring the minimum annual heat gain possible inside a space while maintaining adequate illumination levels (between 300 and 500 lux). In that sense, the results from the analysis becomenbsp;the fitness factor for the optimization process. Figure 6 illustrates the Grasshopper definition of the optimization process and outcome regarding the self-shading element.

The outcome of the process is a taxonomy of window-hosting panels with integrated self-shading elements that are optimized in response to a predefined orientation. The variations in panel sizes and corresponding fenestrations extend the potential for residents to configure the facade appearance through the selection of sizes and relocation of the panels, in addition to window positioning. Moreover, the

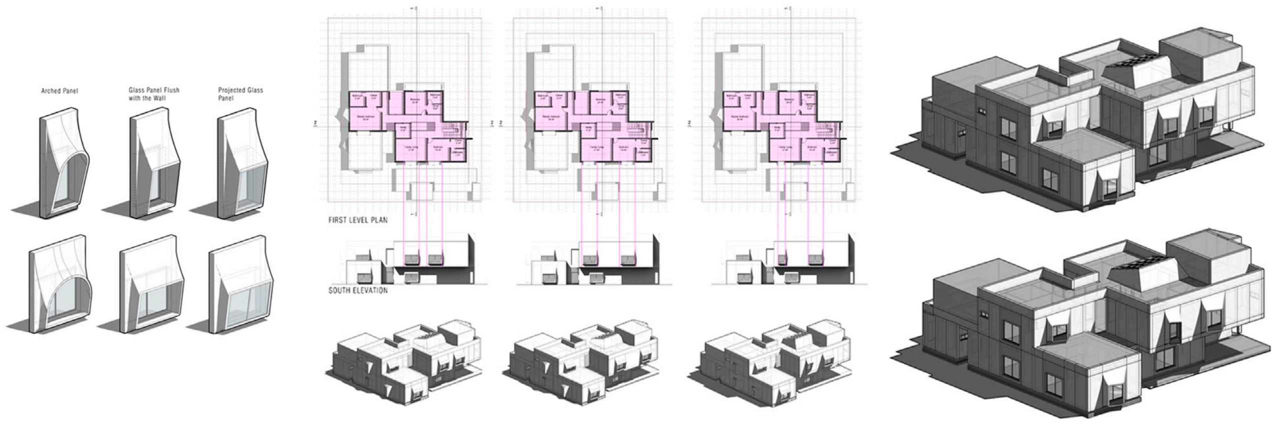

FIGURE 7
Variations in panel size, window, and corresponding self-shading element and its application according to two different orientations: south and west.

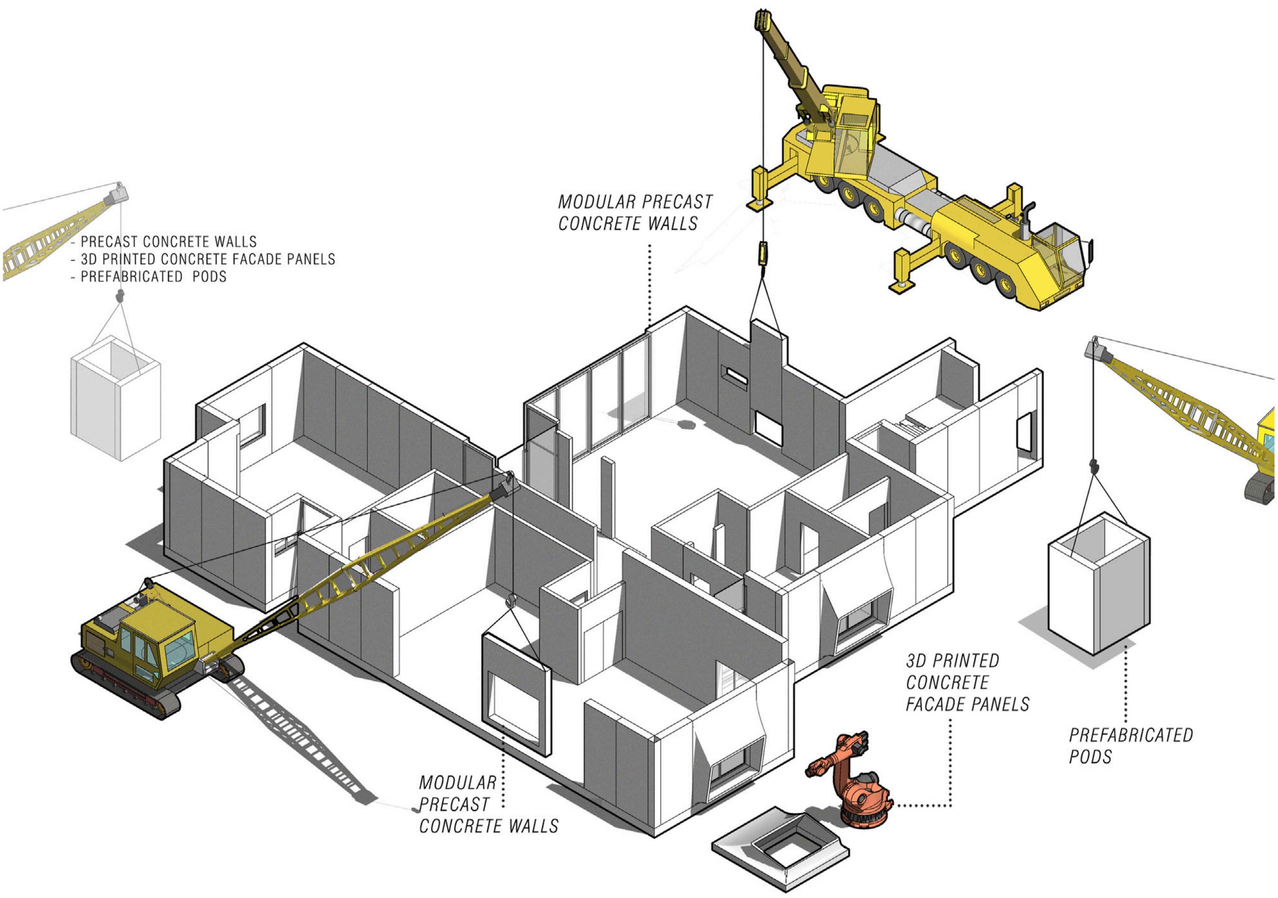

FIGURE 8
Hybrid and collaborative construction process combining precast concrete, prefabricated pods, and 3D printing window-hosting facade panels.

self-shading element leverage privacy thus borrows from the original idea of the *mashrabeya*. Figure 7 represents the possibilities of south-facing panels and their possible applications within the facade of one of the house prototypes. We also represent facade variations in the case of west orientation.

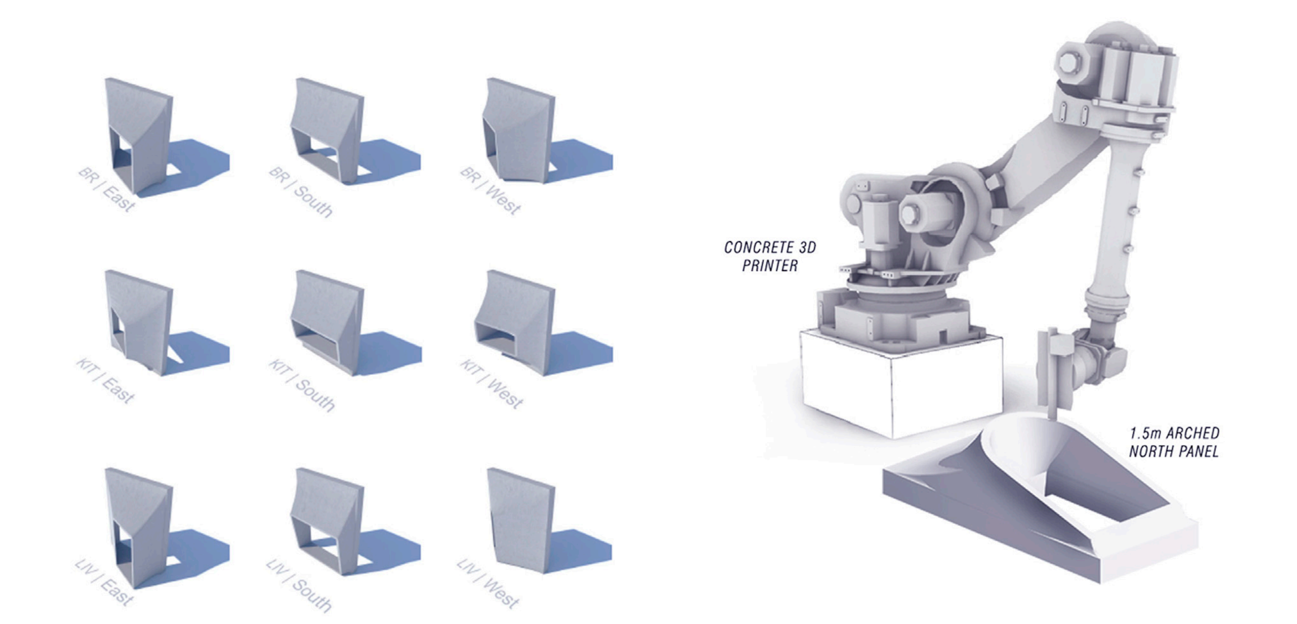

FIGURE 9
3-m-wide window-hosting panels and their variations according to orientation and spatial function.

3.3 Hybrid production approach

The proposed housing prototypes are intended to rely on three different production techniques: first, precast concrete for standard solid panels, structural components, stairs, and floor slabs. Second, modular prefabricated bathroom pods, an approach that has been utilized in the UAE construction market (Lumb et al., 2009). Finally, we anticipate the use of 3D concrete printing for window-hosting panels due to the possible tremendous variations in their shapes as per the orientation. 3D concrete printing has been an active area of research and practice as it is believed to provide enormous potential for the construction industry. It has been argued that 3D concrete printing allows for several improvements in the construction industry regarding the reduction of cost, time, and defects while offering design flexibility. It is also assumed that it can minimize environmental impacts (Hager et al., 2016).

We consider a design to fabrication workflow that can save time and cost. Figure 8 shows a possible production and assembly scheme for a housing unit, relying on the previously mentioned techniques. Figure 9 represents 3-m-wide window-hosting panels and their variations according to the orientation and spatial function. The panels are intended for 3D printing, as per the diagram.

In order to realize the design scheme, we employ a Building Information Modeling (BIM) strategy toward implementing parametric and customizable product families that can be shared between the manufacturer and other component producers throughout the building process. Such a scheme entails standardizing the structure of object information beyond geometry to include specifications for selection and use in analysis, along with material properties. Additionally, the capacity to establish a multiuser environment enables efficient collaboration and data exchange within the design and production teams.

Furthermore, we rely on interoperability for data transfer given that the development of the housing prototypes rely on various digital tools to establish a comprehensive digital model that can incorporate architectural and structural components. For instance, optimized panels are exported as mesh components to Autodesk Revit and then redefined under one parametric family with different types to accommodate all possibilities of orientation, function, and opening size. The purpose is to establish an integrated process where panels can be modified within one approach according to spatial function and orientation toward performing environmental performance simulation.

In order to explore the capacity of such a process, we studied inserting various panel typologies within the skin to evaluate the flexibility and adaptability that is required to respond to various contextual conditions. Accordingly, Revit demonstrates the possibility to investigate the panel materiality, where layers of concrete and insulation are introduced with specific properties, following industry standards. The goal is to develop a digital model that can be effectively simulated for environmental performance.

3.4 Evaluation and environmental performance analysis

As of September 2010, the Pearl Rating System for Estidama Program (Department of Urban Planning and Municipalities (DPM), n.d.) was introduced as a mandatory requirement for all buildings in Abu Dhabi, which is linked to the Abu Dhabi Municipality building that permits the process. Estidama ratings range between 1 and 5 Pearls, where 1 is the lowest and 5 is the highest, depending on a set of clear criteria related to the environmental and energy performance of buildings and

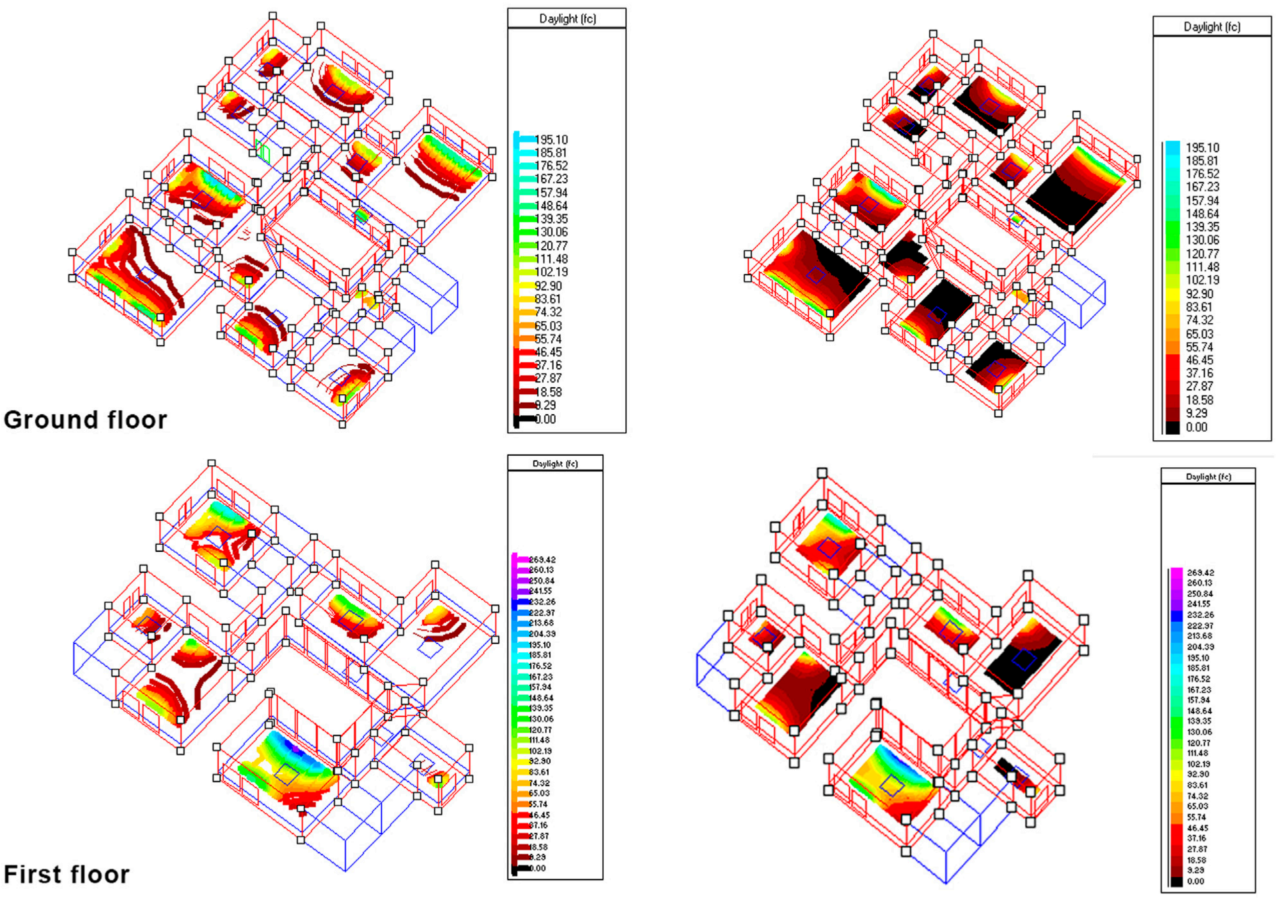

FIGURE 10
Lighting visualization analysis (daylighting).

communities. While the principles of sustainability in Estidama are very similar to the Leadership in Energy and Environmental Design (LEED) criteria, the Pearl Rating System has been regionalized to emphasize the particular concerns relating to Abu Dhabi, with a specific focus on indoor quality, energy saving, innovative design and production practices, and regional and cultural practices.

Given that our proposal is for national housing, we devised a series of strategies to achieve a high level in the Estidama Pearl Villa Rating System for Abu Dhabi—"3 and 5 Pearl." The proposed design strategies focused primarily on the following: first, minimizing construction waste through implementing a modular approach, coupled with employing prefabricated components; second, reducing energy consumption through optimizing window-hosting facade panels; and finally, taking advantage of precast concrete systems to leverage the performance of the building envelope.

In addition to the previously mentioned strategies, more measures have been incorporated and evaluated to achieve the intended Pearl rating, such as

- employing high-performance double-glazing window systems and
- minimizing lighting loads by using energy-efficient light fixtures, occupancy sensors, and dimming controls

3.4.1 Lighting visualization and analysis

Following the implementation of the self-shading facade panels, it was crucial to evaluate the impact of such an approach on the overall quality of natural light within the regularly occupied areas on the floors. This analysis aimed at determining the amount of natural daylighting that would be available in the building based on the previously explained design approach. Given that we had concerns regarding the prioritization of minimizing heat gain over natural lighting quality, it was crucial to perform a natural lighting simulation and analysis for the courtyard housing prototype based on the data of the city of Abu Dhabi. The aim was to determine the levels of natural daylighting and compare these with municipality standards and requirements.

As per Abu Dhabi standards, the acceptable daylight levels range from a minimum of 27.87 foot candles (300 lux) to a maximum of 278.7 foot candles (3,000 lux). For this analysis, the following input parameters were assumed as per typical finishing standards approved by housing authorities:

- reflectivity for floor finishes—20%,
- reflectivity for wall finishes—30%,
- reflectivity for ceiling finishes—50%,
- VLT for glazing—40%, and
- lux level range—minimum 300 lux to maximum 3,000 lux.

Figure 10 offers a graphical representation of the analysis, revealing that adequate levels of daylight without glare have been achieved. It can be noted that the maximum daylighting levels for the ground floor are 195.10 foot candles and 269.42 foot candles for the first floor, which ensures the comfort of the occupants. The peripheral areas of the villa get the desired daylighting level without the inconvenience of any glare. In this sense, we were confident in the approach of integrating the self-shading panels and the role these played in leveraging the buildings' environmental performance by maintaining adequate daylight levels while minimizing natural energy use.

4 Conclusion and future work

There is a remarkable interest in the MENA region and specifically in the UAE to build affordable and environmentally conscious housing projects. Such an interest has been manifested in developing large-scale integrated communities to serve the increasing demands of citizens. However, after working with authorities for 2 years, learning about various challenges, and analyzing some of the projects, we came to the conclusion that the employed design and delivery process is more focused on fast-paced delivery toward the end product rather than on the flexible delivery model that could adapt to accommodate the ever-changing requirements of future inhabitants.

In this work, we present a conceptual approach for the design and delivery of national housing in the UAE that can be considered an alternative approach to the current practices. The proposal is intended to highlight opportunities rather than offer solutions. We believe that there is significant potential in taking advantage of the state-of-the-art design and fabrication technologies, coupled with a critical understanding of the contextual and cultural qualities of dwellings in the region, toward implementing a process that can lead to affordable and customizable housing. Accordingly, the presented approach is shaped by three main strategies: first, a modular design approach that can act as a reference to develop flexible and scalable housing solutions; second, a computational statement for facade optimization toward more efficient building performance; and third, a comprehensive relationship between design and notions of prefabrication that combine precast concrete, modular utility pods, and 3D concrete printing toward exploiting its potential in efficiently realizing buildings.

While we believe that the presented work is successful theoretically, there are a series of drawbacks that can be identified. First, the outcome of the optimization process, as represented, has been validated theoretically for printability but has not yet been realized. We are in the process of establishing a 3D concrete printing laboratory to experiment with the topic and investigate the development of a smooth transition from design to fabrication. Second, we have not yet performed a comprehensive energy analysis to investigate the validity of some of the design decisions, as we only focused on the performance of self-shading elements and their impacts on the lighting quality. Finally, we have not had the chance to evaluate the cost-effectiveness of the proposed housing prototypes, which can play a major role in realizing such an approach. Nevertheless, we aim to continue working on issues related to affordability and flexibility of housing through the application of cutting-edge technology toward housing that can respond to global challenges.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material; further inquiries can be directed to the corresponding author.

Author contributions

BM was responsible for conceptualization of the research project, writing of the manuscript, and reviewing the design approach. ME orchestrated roles between authors and wrote the review on Emirati housing, and helped with environmental performance analysis. RZ worked on modeling, developing drawings and diagrams, and computational designing and simulation. RH helped with the review of the article, developing the literature review, and putting various sections together. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Cohousing design guidelines for better social integration in the United Arab Emirates

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Considering cohousing as a new typology in the United Arab Emirates' (UAE) housing market is a challenge due to the cultural and societal dimensions. However, the variety of societies in the Emirates reflecting various habits, experiences, and traditions can allow testing such new types of housing which can be adapted to the local context, considering the needs of the society. This study aims at developing design guidelines for future cohousing in the UAE, considering the pillars of the Estidama program, i.e., social, cultural, economic, and environmental aspects, in addition to the role of architecture design. The present study is based on an empirical investigation from the viewpoint of future cohousing residents in the UAE. Semi-structured interviews considering 87 individuals were conducted. Moreover, a focus group discussion targeting eight professionals was performed. Furthermore, the Quality Function Deployment (QFD) method was applied to include the people's voices directly when developing the design guidelines for cohousing in the UAE. The study showed that the aspects of culture and privacy are crucial in the future of cohousing in the UAE. In addition, providing local facilities such as majlis and praying rooms is vital to consider. Moreover, other aspects such as sustainable design, universal design, and safety are also valuable. For the outdoor environment, the study highlighted the importance of urban design quality, landscape solutions, shading, and natural ventilation strategies in outdoor spaces. Future cohousing in the UAE is expected to enhance social interaction and contribute to sustainability in the long-term perspective.

KEYWORDS

architecture design, cohousing, quality function deployment, social interaction, United Arab Emirates, urban design

1 Introduction

Providing shelter is one of the most critical needs of human beings and is considered one of the fundamentals in Maslow's hierarchy of needs. Humans' demands are genuinely being developed, and the concept of housing has been shifted from being of basic and physical shelter to a place to create, save, and practice memories in a comfortable and safe place (Cowans et al., 2021). Kaufman (2006) stated that safety when providing housing is a necessity for the family. Without a decent place to live, people cannot be productive members of the community, children cannot learn, and families cannot thrive. Additionally, housing is one of the core domains within the framework of integration into society (Ager and Strang, 2008). According to Ragette (2006), shelter satisfies a human's physical and psychological needs. Physical needs are represented as protection against unpleasant weather (heat and cold) and different attacks from others in the surroundings. Psychological needs usually come after satisfying physical needs, such as security and self-expression.

Over the decades, different housing types, forms, and definitions have been developed worldwide, attempting to consider the needs of domestic people. Housing types, such as courtyard housing, townhouse, towers, and villas, are common housing typologies. Another categorization of housing is divided into attached and detached housing forms. A third is categorized into low-, mid-, and high-rise housing forms. Meanwhile, considerable interest has been found in developing other contemporary housing types based on a sharing approach (Babos et al., 2020). In the second half of the 20th century, a new trend of collective forms of housing with the sharing approach appeared in Europe, which led to a wide variety of alternative housing models. Housing forms such as collective living, communal housing, collective initiatives, cooperative housing, and collective living are examples (Lang et al., 2020) focusing on the sharing approach, which became a fundamental issue of contemporary urban housing (McIntosh et al., 2010). Hence, using different terms expressing the sharing approach is sometimes contradictory or overlapping (Vestbro, 2010).

To understand the idea behind developing different collective forms of housing, one must shed light on the concept of an intentional community, which refers to a relatively small group of people who have created a whole way of life to attain a particular set of goals. Intentional communities have emerged as a group of people consciously and purposefully coalescing to realize a set of aims. This group attempts to create a unified way of life, i.e., one lifestyle that can be applied to the whole community; hence, unlike organizations or social movements, they are intentional communities (Shenker, 2011). Intentional communities can include housing types such as ecovillages, cohousing, urban housing, housing cooperatives, conference and retreat communities, rural homesteading communities, spiritual communities, religious communities, and income-sharing communes (Sanguinetti, 2013).

Cohousing, as a definition, has different meanings; one reason behind that is the use of the term in different countries, languages, cultural backgrounds, etc. (Vestbro, 2000), and therefore, Vestbro called for the need to find terms that could be used worldwide to avoid misinterpretation (Vestbro, 2010). The most used terms for "housing with shared facilities and other shared characteristics" are "co-housing" and "cohousing" (Babos et al., 2020). Based on current research, Vestbro (2010) defined cohousing as housing with common spaces and shared facilities. The author argued that the co-housing concept does not precisely state what "co" stands for; it could be collaborative, cooperative, collective, or communal (Vestbro, 2010). Babos et al. (2020) recommended separate definitions for the two terms. The co-housing term is a general expression; several different models can be distinguished under this broader concept. The author stated that housing forms such as collective self-build housing, collective self-help housing, collective living, community-led housing, condominiums, collaborative housing, eco-village, eco-district, and intentional community are examples of co-housing. On the other hand, cohousing is a particular form of housing with shared characteristics. Such shared characteristics must apply four features simultaneously: sharing spaces, activities, creation, and tenure (Babos et al., 2020). In co-housing, the residents participate in creating the communities. Residents typically collect multiple households with shared land, facilities, and public space with their neighbors without invading each household's privacy. The primary purpose of co-housing is to create a social environment. It may differ in size, location, design, and type of ownership. They have, however, common characteristics (McCamant and Durrett, 2011), such as 1) a participatory development process; 2) a design that facilitates community (neighborhood design); 3) common facilities (shared areas that are designed for daily use); 4) complete resident management (the residents manage the development and decision-making of their concerns at the place in community meetings); 5) non-hierarchical structure and decision-making; 6) a separate income source (residents have their own income), making it different from communal living (George, 2006). Co-housing development consists of private houses and common facilities where all activities and socializing occur. The specific features of common facilities depend on the interest of residents. Still, it usually has a common kitchen, laundry, living room, dining area, playroom for children, community meetings area, and guest rooms. The outdoor area can include a common garden, common socializing and meeting spots, and parking lots (Sanguinetti, 2013).

Co-housing aims to create a community within a neighborhood, with shared facilities, without sacrificing the privacy of the people (Bamford, 2008). One of the reasons for developing collective housing is the wish to design a community for children by creating a safe, encouraging environment, a "child-friendly environment." Children's movements are often restricted, with play beyond the front fence restricted as it is unsafe or believed to be so (Bamford, 2008), while in cohousing, children have more freedom and opportunities to play and interact with other children because they live close by and know their neighbors well (Vestbro, 2000; McCamant & Durrett, 2011).

With the technology boom after the industrial age, lifestyle has changed drastically and changed the way people interact with each other (McGraw-Hill, 2022). For example, using technological devices, including computers, mobile devices, and smartphones, contributed to shifting the meeting zone from physical to virtual through using different online platforms. In addition, working remotely from home changed the way of living and the way of interacting with others during the day (Gutman et al., 2022). On the other hand, technology addiction can lead to social isolation, characterized by a lack of contact with other people in everyday life (Hosale, 2013). According to Alghamdi (2016), anyone who browses the internet frequently is likely to spend less time with friends and family than non-internet users. Through architecture and different types of co-housing, it is possible to change habits and solve the problem of isolation by facilitating a community that allows people to socialize and interact with each other, bringing back the sense of a neighborhood and community and creating spaces where people feel safe and feel like belonging and integrate with others even during challenging periods such as COVID-19 (Arroyo et al., 2021).

Considering different housing forms categorized under the term co-housing (Babos et al., 2020), one of the early examples in the 1930s is the Swedish word kollektivhus (literally collective building), which is the most frequently used term for housing with shared facilities (Vestbro, 2014). The aim was to reduce women's housework so they could retain gainful employment even when they get married and have children. In the 1960s, the modern type of cohousing originated in Denmark as some families were dissatisfied with existing housing and communities that did not meet their needs (Caves, 2004). It blossomed exponentially in the 1990s in North America, following the publication of the book "Co-housing: A contemporary approach to housing ourselves" by two American architects Kathryn McCamant and Charles Durrett in 1988, who adopted the concept from Denmark (McCamant and Durrett, 1988). Durrett and McCamant first developed the term cohousing in the United States. Afterward, cohousing increased in popularity around the world, and many projects have been established in countries such as Sweden, Germany, the Netherlands, Australia, Canada, the United States, Spain, France, Italy and the United Kingdom, and Asia (Bamford, 2008; Sanguinetti, 2013; Arbell, 2022).

1.1 Cohousing in the United Arab Emirates

The United Arab Emirates (UAE) has considered and embraced a range of approaches, leading to the current flourishing economy. Diversity in the UAE is the significant difference in how residents identify with different subjects. The country has over 200 nationalities as residents, implying the variation in ethnicity, culture, background, gender, beliefs, etc. Although the UAE has significant experience integrating different ethnicities, the concept of cohousing is yet to be promoted in the housing market. Few individual initiatives in Dubai promoted and adapted the concept of co-living differently to fit the local needs in the housing market. The new vision of co-living in Dubai is a new trend among millennials for renting shared apartments to save money and live with like-minded people. It consists of a well-designed, fully furnished place, with utensils and utilities covered by one bill (Coliving, 2023). The UAE is a modern country influenced by globalization, making it a reflection of all civilizations without preserving its own identity.

The standard housing types in the UAE consist of apartments/condominiums and villas/landed houses. The major cities for the housing market are Dubai, Abu Dhabi, and Sharjah (Mordor Intelligence, 2023). The type of tenure is divided into 1) owned housing, where the housing unit is built on the property of the owner. The government-subsidized housing and government villas that are owned by UAE nationals, and the owner of the same resides in them, are also included in this type; 2) lease housing, where the housing unit is not furnished, and the owner is renting it directly from the owner or his/her agent; 3) furnished lease, where the housing unit is furnished and leased to the owner directly from the owner or his/her agent; 4) housing provided by the employer, where the employer provides the house to the holder, whether the house is owned or rented by the employer; and 5) other housing types such as gifts and donations (SCAD, 2023). The average housing prices in dirhams per square foot in Dubai, for example, in the period 2008–2020, varied from 1.95 to 911 K, where sales of off-plan properties in Dubai registered strong growth in 2021 (Mordor Intelligence, 2023).

Meanwhile, the traditional Arabic city used to share what is so called a "sense of belonging," where all citizens are strongly tied to what they feel is part of them. Bringing back essential core values and positive habits means understanding what formed the complex urban fabric back then. Considering the ongoing urban development in the UAE and different types of residential areas hosting various ethnicities with diverse cultures and backgrounds, there is a need to develop new housing alternatives that can be added to what existed in the market. This new housing alternative should consider social, cultural, economic, and environmental aspects, the four pillars of the so-called "Estidama," which means the sustainability program applied in the UAE (Estidama, 2010). Designing co-housing in the UAE is a challenge of making new typologies that fit the local context, considering aspects such as different ethnicities and demographics, various cultures, and new building technologies. By conducting an empirical investigation, this study aims at developing design guidelines for future cohousing in the UAE, considering the pillars of the Estidama program, i.e., social, cultural, economic, and environmental aspects, in addition to the role of architecture design.

1.2 Estidama program

"Estidama," which means "sustainability" in Arabic, aims to develop more sustainable, cost-effective communities, cities, and global companies while balancing Estidama's four pillars: environmental, economic, cultural, and social aspects. Estidama's goals are reflected in Plan 2030 and other Urban Planning Council (UPC) policies, for example, the Development Code. Estidama was founded in 2008 and is the first program of its type in the Middle East. Estidama's immediate focus is on the quickly changing built environment. The UPC is making substantial achievements in this field to affect projects under design, development, or construction. The Pearl Rating System is one of Estidama's primary endeavors (Estidama, 2010). There are seven fundamental categories of sustainable design, according to Estidama: integrated development process, conserving natural environment, livable communities, precious water, resourceful energy, stewarding materials, and innovating practice.

The ultimate goal of Estidama is to preserve and enrich the physical and cultural identity, and it has already tackled many aspects, such as building the city and adequately using available resources, all in an effort to attain a sustainable state of living. By working closely with all stakeholders, Estidama has already improved the mindset and implementation practices of the construction industry and will continually develop to encourage societal improvement. As for outcomes and impacts, the Pearl Rating System provides regulatory guidance on design, construction, and operational performance. Meanwhile, sustainability principles are also embedded in new planning documents through Estidama's continual improvement and participation in policy development. Estidama buildings, for example, have been designed to reduce energy by 31% and use 37% less water. More impressively, 65% of construction waste has been diverted from landfill. There are also unquantifiable impacts, such as improved health of buildings and quality of life for residents, due to mandatory reduction of unhealthy materials and the encouragement of passive design measures. These and many other improvements occur at all scales, from single homes to whole communities, through the Pearl Rating System for villas, buildings, and communities. As Estidama becomes more recognized, it is also being implemented in other Emirates and countries in the region, including Bahrain and Seychelles (Urban Agenda Platform, 2023).

2 Materials and methods

As mentioned previously, the present study is based on an empirical investigation from the viewpoint of future cohousing residents in the UAE considering the pillars of the Estidama program, i.e., social, cultural, economic, and environmental aspects, in addition to the role of architecture design. Semi-structured interviews with 87 individuals were conducted. Moreover, a focus group discussion targeting eight professionals was performed. Furthermore, the quality function deployment (QFD) method (Akao, 1997) is applied to include the people's voices directly when developing the design guidelines for cohousing in the UAE.

2.1 Semi-structured interviews

The semi-structured interviews aim to investigate the needs of the people when developing cohousing communities in the UAE. The advantage of using semi-structured interviews (Hitchcock & Hughes, 1989) is that the interviewer controls the process of obtaining information from the interviewee. Still, it is free to follow new leads as they arise (Bernard, 1988). In this study, interviews with 87 individuals were conducted face-to-face and then transcribed, coded, and analyzed. The design of the semi-structured interviews is based on the Estidama sustainability pillars, as mentioned previously. The interview form includes general questions about age, gender, the city of residency, etc. Moreover, the form includes 18 questions divided into Estidama's four pillars, in addition to the role of the design, as shown in Table 1. The target sample tends to be mixed, consisting of local Emiratis and residents interested in the concept of cohousing or who might be future residents in cohousing projects in the UAE, investigating their potential needs in such a type of cohousing. The interview process considers people of all ages with various ethnicities, cultures, religions, etc. The sample included university students, public and private employees, and people in public facilities such as university campuses, malls, and offices. In this study, about 69% of

TABLE 1 Semi-structured interview questions based on Estidama's four pillars.

Q	Parameter	Question
1	Culture	To what extent would you like to live in a community where all neighbors know each other, share activities, and meet others?
2		To what extent are you interested in sharing daily life common facilities (majlis, kitchen, dining rooms, and BBQ spaces) with your neighbors?
3		To what extent are you willing to adopt new habits and culture, such as cooking together, doing common activities, and co-parenting?
4		To what extent would you live in a cohousing that preserves and enhances your privacy and your society's values?
5		To what extent would you like to invite guests to the community majlis (common guest room) rather than your private one?
6	Environment	To what extent are you interested in living in sustainable communities that apply friendly energy solutions for a better environment?
7		How important is providing shaded and ventilated sitting areas for outdoor activities?
8	Social	How much do you engage with your neighbors performing common activities?
9		Your kids spend more than 3 h a day chatting on electronic devices solely
10		Your kids spend more than 3 h playing with other kids outside (after school)
11		How much do you think people are isolated from their environment by spending more time on social media than interacting with family members?
12		By living in cohousing, to what extent do you agree that your kids will spend more time in outdoor spaces (than time spent on social media) to interact with other kids safely?
13		By living in cohousing, how much do you agree to have common indoor and outdoor facilities (both for adults and kids) that facilitate different activities next to your private unit?
14	Economic	To what extent do you agree to have a 10% smaller private apartment in a collaborative community and have, in turn, more space for common facilities to reduce living costs?
15		To what extent do you agree to share service fees, cleaning equipment, drilling machines, etc., with your neighbors to reduce the cost of living?
16		To what extent do you agree that cohousing is more money-saving than individual houses?
17	Design	To what extent do you agree to have two courtyards (private and public)?
18		To what extent do you agree to be involved in the planning and designing phase (designing your housing unit)?

respondents were local Emiratis, while approximately 31% were residents, and all were living in Dubai and Sharjah, which were the targeted geographical locations in this study. The purpose of the sample is exploratory, not representative. According to Denscombe (2014), in exploratory samples, the research scale tends to be smaller, which is due to the likelihood that every person in the sample will be studied in great depth, and the size of this sample type is not governed by matters of accuracy but by considerations of how informative the sample is. The sample size should only be sufficient for the researcher to feel that adequate information was collected (Denscombe, 2014). In this study, about 89% of respondents were local Emiratis living in Dubai and Sharjah, while the rest were residents in the two cities.

The design of the semi-structured interview form was based on the Estidama sustainability pillars, i.e., cultural, social, economic, and environmental aspects, in addition to the role of architecture design. As for the social aspect, five questions were designed to investigate whether or not the respondents 1) are keen to live in cohousing; 2) would like to share daily life common facilities; 3) adopt new habits and culture; 4) would like to live in a cohousing that preserves and enhances privacy; 5) would like to invite guests to the community majlis (a common guest room). Regarding the environmental aspect, two questions were considered to investigate the level of interest in housing units providing friendly energy solutions, shading, and ventilation strategies. In the case of the social aspect, six questions were considered to investigate social engagement with others, both for adults and kids, in addition to the risk of social isolation and consideration of common facilities next to the private units. As for the economic aspect, three questions were designed to investigate to what extent the interviewees are interested in the idea of saving by sharing (Vestbro, 2012). Investigating the role of the design aspect in cohousing includes two questions related to privacy in the architecture design, as well as the role of user involvement in the design process.

The authors were interested in collecting ordinal data to reflect on the four aspects of the Estidama sustainability program. Therefore, a five-point Likert scale was used denoting least favorable, less favorable, neutral, more favorable, and most favorable. The idea of using a five-point Likert scale was that it was comparatively easier to understand, considering a neutral standpoint and opposing extremes as positive or negative reviews.

2.2 Focus group discussion

To gain input on how cohousing can be adapted to the social, cultural, and environmental conditions in the UAE, a focus group discussion was applied. Moreover, different challenges facing the concept of cohousing in the UAE were discussed and elaborated. Focus group discussion (Morgan, 1988) is a method facilitating need assessment (Tipping, 1998). The selection criteria were based on considering professionals (n = 8 persons) with similar backgrounds, interests, and experiences, mainly in architectural design and urban development. The sample was organized to have input from both the UAE and Sweden. The reason for inviting Swedish professionals was to gain insight and experience from a European country with a solid experience in different types of cohousing and various intentional communities. Four Swedish architects and urban designers and another four from the UAE accepted the invitation.

To achieve the aim of the focus group discussion, the following triple agenda was introduced: 1) architectural design considerations, 2) cultural and social considerations, and 3) urban design considerations. The meeting was organized to be online (Edmunds, 1999) and planned for 3 h, divided into two sessions. The first session consists of a presentation showing the project's aim, objectives, procedures, etc., followed by a discussion to develop the project. The second part of the meeting was planned to be an open discussion to have input on the aforementioned triple agenda. To achieve the triple agenda throughout the meeting, the following questions, among other inquiries, were raised for further discussion: 1) what are the main obstacles/barriers/challenges/priorities affecting cohousing architectural design in the UAE? 2) How can the architectural design of future cohousing in the UAE better facilitate cultural and social aspects? 3) How can outdoor spaces of the cohousing play an essential role in facilitating social integration while considering privacy? (4) What environmental solutions can be applied in the future cohousing of the UAE?

2.3 Triangulation of empirical results

This study uses content analysis (Baxter, 1994) to analyze the outcome of the focus group discussion, focusing on expectations of how the future cohousing in the UAE will look. The output of the focus group discussion will be compared with the outcomes of semi-structured interviews via Quality Function Deployment.

2.4 Quality Function Deployment (QFD)

Quality Function Deployment (QFD) is a methodology that helps translate customer needs into design requirements to ensure that the output, whether a product or process, meets these needs (Erdil and Arani, 2018). Its applications are primarily found in design-related efforts, and many still limit QFD use to product design and development (Franceschini, 2002). The International Organization for Standardization (ISO) describes QFD as "a method to assure customer or stakeholder satisfaction and value with new and existing products by designing in, from different levels and different perspectives, the requirements that are most important to the customer or stakeholder" (ISO, 2015). The name was derived from its Japanese roots: hinshitsu cinema Tenkai (Akao, 1997). This method allows all stakeholders to exert power in the design process or modification of the existing, where every voice is counted, and the customer is put first. Moreover, it focuses on a significant critical view to putting all powers on making it the best way. QFD opens insights on critical points to customers that companies did not pay enough attention to, resulting in a highly unexpected prioritization that differs from the conventional wisdom held by the company and many of the participants before engaging in QFD (Hauser et al., 2010, page 07). Varolgüneş and Canan (2018) reported that the "architectural design process entails many problems due to its versatility. User demands, environmental factors, structure acquisition, processes, and project teams vary even for designs of the same structure type. Despite the diversity of these factors, the

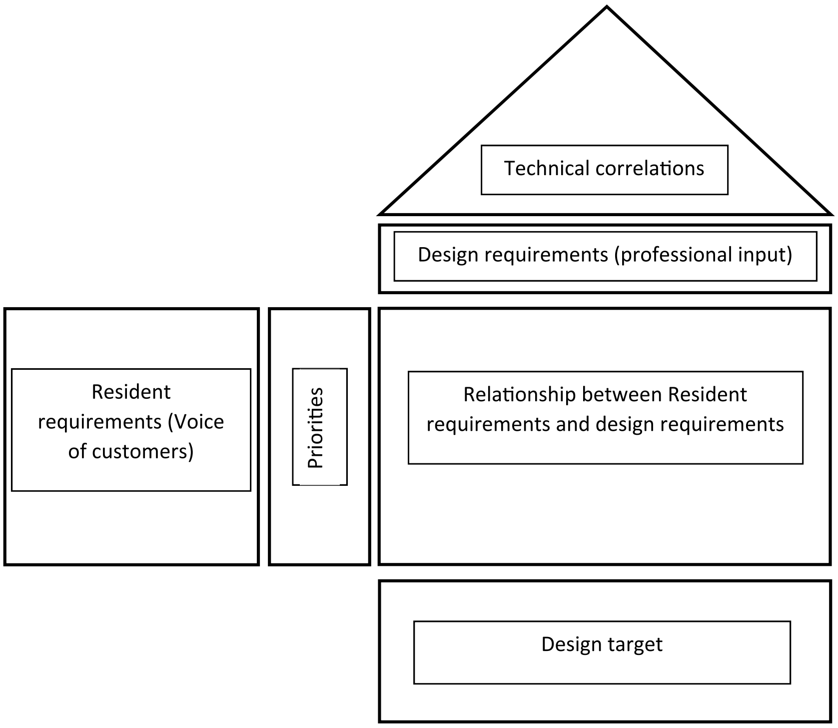


FIGURE 1
House of Quality (HOQ).

architectural design process usually develops in a designer-oriented way." This entails that the client's needs about the design are lacking in the outcome, resulting in rework and excessive meetings that add up in cost and the time required to finish the whole process.

The House of Quality (HOQ) is the matrix or tool used to present the technical response of the given rows of requirements; it is also a communication tool between the QFD team and the management (Varolgüneş & Canan, 2018). The development process starts with understanding customer needs and how well the company products or services respond to them from customers' perspective. The VOC is represented in the WHATs section of the matrix on the left side (Figure 1). The WHATs section identifies and classifies customer needs and desires that should be considered in the final design and/or product. The relative weight of each requirement is obtained from a survey or interview conducted with the customer, in which they rank how important each of them is. The middle part of the HOQ is the treatment of each need into a technical specification that is ranked by a strong, moderate, and weak scale symbolized by ●, ○, and ▽ and given a weight of ±9, ±3, and ±1, respectively. The triangular roof of the house indicates the correlation between various technical treatments to have an idea about how the treatment of a particular need might affect or repel the effectiveness of others. The remaining part at the bottom resembles the determination of targets and relative weights using a simple calculation of each column (Figure 1). In this study, the critical points of the cohousing QFD were categorized under the same main categories that semi-structured interviews were based on, i.e., cultural, social, environmental, economic, and design aspects. The data analysis obtained relative weight when translating the Likert scale results to a 1–5 scale. The inputs for the WHATs are as follows:

- Bringing back the sense of the old Fareej (traditional housing)
- Sharing daily life facilities
- Adapting new habits
- Preserving and enhancing social values
- Sustainable building
- Protection from the weather conditions in outdoor space
- Inviting guests to the community majlis (guest room)
- Knowing neighbors
- Kids going back to the urban space
- Time spent on social media

These WHATs are placed on the left side of the HOQ (Figure 1), and the HOWs form the horizontal belt of technical requirements that experts thought are most relevant and beneficial to the design process of co-housing. These HOWs have target values, either quantitative or qualitative; they are set to achieve a goal and to use it to benchmark with other case studies. The goal of benchmarking is to analyze what they did to succeed and what design considerations were the most important. The HOWs or the design requirements are derived from the focus group discussion (see Section 2.2). The central interrelationship section used the scale of the symbol (●, ○, and ▽) to study which design elements affect a critical point the most; one critical point might be affected by more than one design element. Shading pathways, for instance, are affected by thermal comfort study and innovative design. As the concept of cohousing is new in the UAE, no comparisons with other

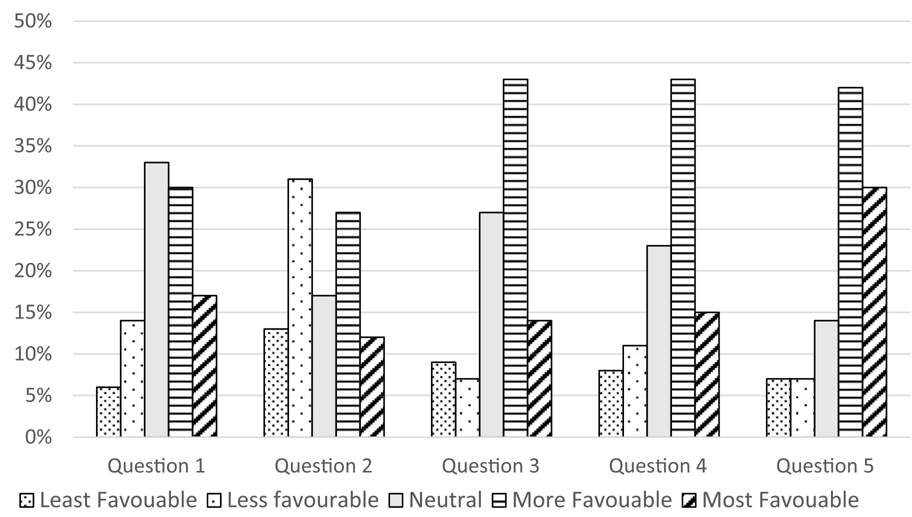


FIGURE 2
Cultural parameters that affected the concept of developing cohousing in the UAE.

cohousing projects were carried out; therefore, "competitive evaluations" in the HOQ are not applicable.

3 Results

This section presents the results divided into three parts. The first part introduces the outcomes of the semi-structured interviews related to the pillars of the Estidama program. The second part of the results presents the outcomes of the focus group discussion related to how cohousing can be adapted to the UAE's social, cultural, and environmental conditions. The third part illustrates the QFD outcomes.

3.1 Parameters affecting the development of cohousing in the UAE

3.1.1 Cultural parameters

Figure 2 illustrates that about 47% of the samples favor living in a community where all neighbors know each other, share activities, and meet others. In contrast, only 20% do not to prefer to live in such a community, whereas approximately 33% are neutral and have no preferences (see question 1 in Figure 2). Moreover, about 39% of the respondents are interested in sharing common daily life facilities such as majlis, kitchens, dining rooms, and BBQ spaces with their neighbors. In contrast, 44% do not favor sharing such facilities, and 17% are neutral and have no preferences (see question 2 in Figure 2). The results also show that about 57% of the interviewees are willing to adopt new habits and culture, such as cooking together, doing everyday activities, and co-parenting. On the other hand, only 16% favor not adopting new habits and cultures, whereas 27% do not indicate their preferences (see question 3 in Figure 2). The results also highlight that approximately 58% of the studied samples would like to live in a cohousing that respects privacy and society's values. In contrast, only 19% do not favor and prefer to live in such a community that respects privacy and society's values, whereas approximately 23% are neutral and with no preferences (see question 4 in Figure 2). The study shows that approximately 72% of the respondents favor inviting their guests to the shared guest room rather than to their private room at home, whereas a few (about 14%) favor inviting their guests to the living room in the residential unit, and approximately 14% favor not to identify their preferences (see question 5 in Figure 2).

3.1.2 Environmental parameters

In the context of exploring whether or not the interviewees are interested in environmental parameters in the future design of cohousing in the UAE, Figure 3 shows that the majority of the interviewees (86%) are interested in living in sustainable communities that apply friendly energy solutions for a better environment. On the contrary, very few interviewees (5%) are not interested in such environmental solutions, whereas approximately 9% prefer not to express their opinions (see question 6 in Figure 3). The results also illustrate that it is vital in shared outdoor spaces to consider shaded and ventilated sitting areas to protect from solar radiation and reduce the amount of heat stress (approximately 47%). On the contrary, a considerable number of answers (approximately 38%) do not prioritize having shading and ventilation in the shared outdoor spaces, whereas approximately 15% decide to be neutral (see question 7 in Figure 3).

3.1.3 Social parameters

As for the social parameters, Figure 4 illustrates that most of the answers (49%) stated that engaging with neighbors performing common activities is the least favorable. In contrast, only 31% favor engaging with the neighbors, whereas other interviewees (20%) preferred to be neutral with their answers (see question 8 in Figure 4). The results show that about 57% of the interviewees consider that their kids spend more than 3 h using online chatting platforms daily, and other interviewees (30%) preferred to be neutral (see question 9 in Figure 4). In the same

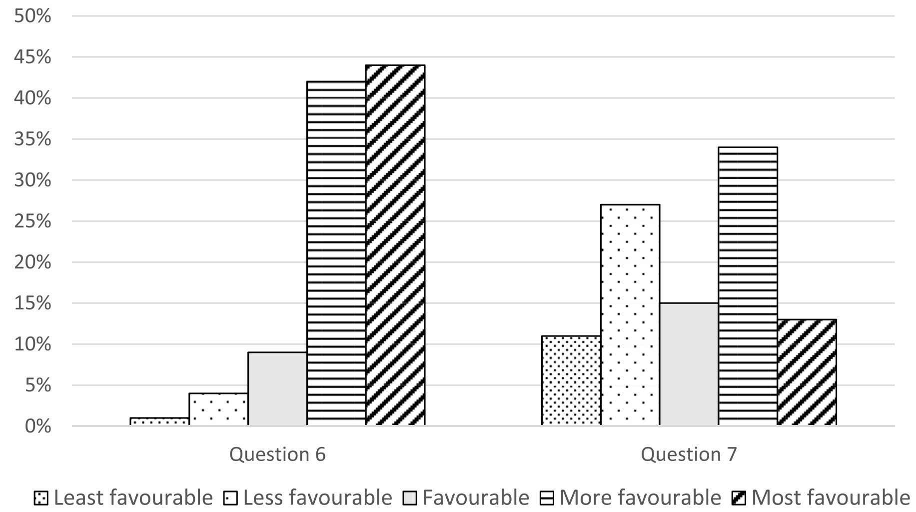


FIGURE 3
Environmental parameters that affected the concept of developing cohousing in the UAE.

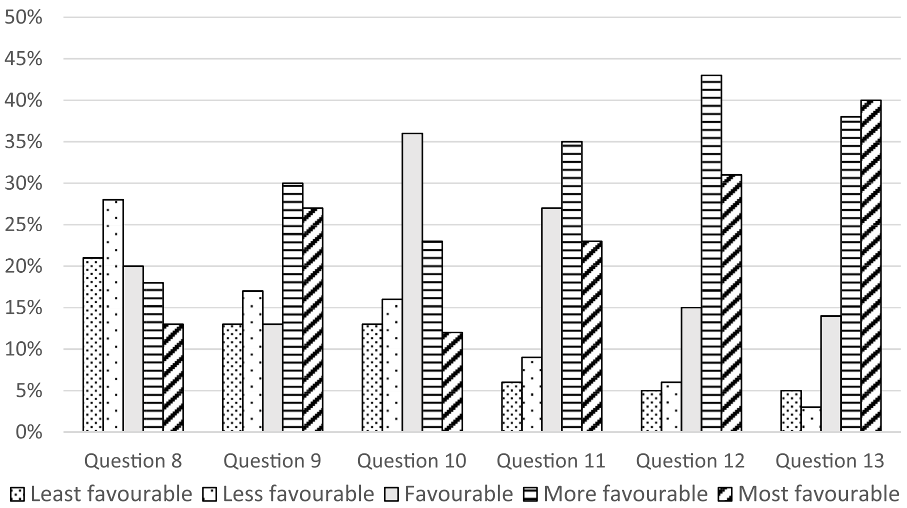


FIGURE 4
Social parameters that affected the concept of developing cohousing in the UAE.

context, fewer interviewees (35%) consider that their kids spend more than 3 h (after school) playing with other kids outdoors, and other interviewees (35%) preferred to be neutral (see question 10 in Figure 4). The results reveal that 58% of the samples consider that people are isolated due to the massive time spent on social media than the time spent interacting with families. On the contrary, only 15% do not believe that people are socially isolated due to the massive time spent on social media, whereas about 27% decided to be neutral (see question 11 in Figure 4). Many interviewees (74%) think that by considering cohousing as an option, the kids will spend more time in outdoor spaces (than time spent on social media) to interact with other kids safely. On the other hand, 11% do not believe that the kids will spend more time outdoors than indoors in the cohousing, whereas 15% preferred to be neutral (see question 12 in Figure 4). By considering cohousing as an option, the results show that 78% agree to have common indoor and outdoor facilities (both for adults and kids) that facilitate different activities next to the private units. On the other hand, only 8% do not agree to have common indoor and outdoor facilities next to their private units, whereas about 14% show no preferences (see question 13 in Figure 4).

3.1.4 Economic parameters

Regarding the economic parameters, Figure 5 shows that about 45% of the answers agree to have a 10% smaller private apartment in a collaborative community and have, in turn, more space for

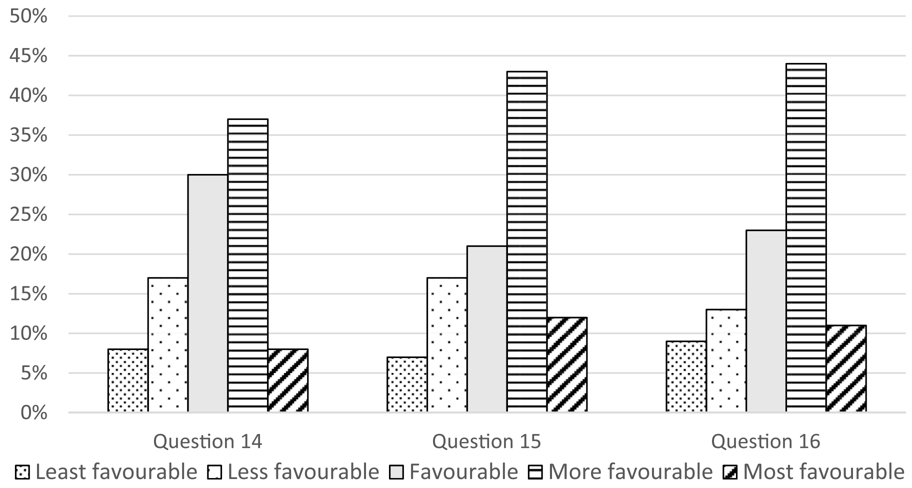


FIGURE 5
Economic parameters that affected the concept of developing cohousing in the UAE.

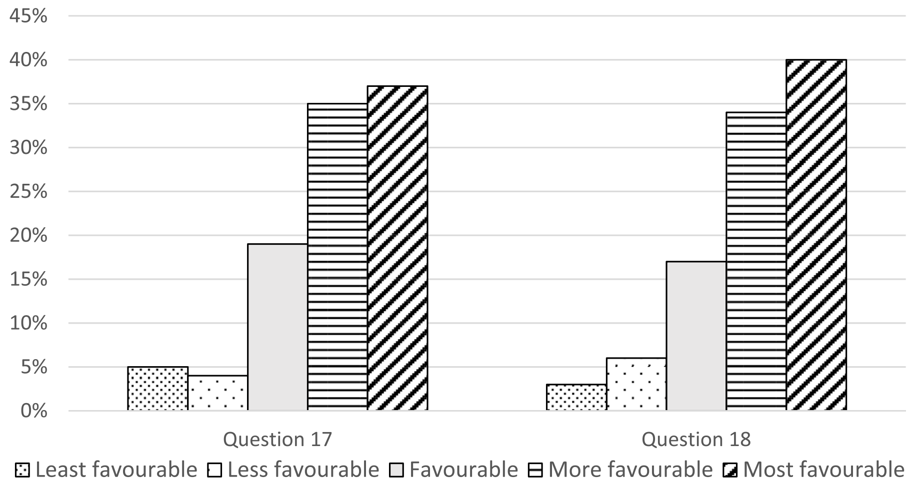


FIGURE 6
Design parameters that affected the concept of developing cohousing in the UAE.

common facilities to reduce living costs. On the contrary, about 25% disagreed with living in a limited-size apartment, whereas about 30% of the answers were neutral (see question 14 in Figure 5). The results also reveal that the majority of the respondents (55%) agree on sharing service fees, cleaning equipment, drilling machines, etc., with the neighbors to reduce the cost of living for the community (see question 15 in Figure 5). In contrast, only 24% did not agree on sharing stuff with others, and about 21% of the answers were neutral (see question 15 in Figure 5). The results illustrate that many interviewees (55%) agree that cohousing is more cost-effective than individual houses. On the other hand, about 22% of the samples disagreed with the approach of saving by sharing, and only 23% of the answers were neutral (see question 16 in Figure 5).

3.1.5 Design parameters

Regarding the design parameters, the results show that privacy has an important role in the future design of cohousing in the UAE. Figure 6 illustrates that most of the answers (72%) agree that the housing units of cohousing should have two courtyards (private and public) for privacy reasons. In contrast, only 9% disagree with this approach, whereas other interviewees (19%) prefer to be neutral with their answers (see question 17 in Figure 6). The results also illustrate that the sample is highly interested in participating in the design process. In this context, the results reveal that the majority of the sample (74%) would like to be involved in the planning and design phase of the cohousing project. Only 9% of the respondents disagreed with being involved in the design process, whereas about 17% preferred to be neutral (see question 18 in Figure 6).

3.2 Adapting cohousing to the UAE conditions

3.2.1 Architectural design considerations

The focus group discussion—consisting of Swedish and UAE groups—highlighted that the architectural design of future cohousing in the UAE should be given a high priority. The input from the Swedish invited group mostly focused on 1) providing new functions to be added to the cohousing, such as majlis (reception and guest room), praying room, activity room for women, office hall for online working, study room for teenagers and playroom for kids, and common kitchen attached to a separate dining room; 2) facilitating innovative design that should reflect the society's identity; for example, a courtyard system can be applied and tested to produce local architecture; (3) prioritizing safety requirements, especially for kids' indoor and outdoor spaces. It is also crucial to consider a universal design with high standards to make the building and its shared facilities accessible and safe to all, including the elderly. On the other hand, the input from the group in UAE mainly focused on 1) clearly identifying the private spaces from the public spaces to be able to draw a clear line between common facilities and private units. In this context, mixing the circulation between the common and private facilities is not recommended and 2) considering mixed building geometries (attached and detached units) with courtyards for various architectural purposes. The number of units, however, needs to be specified based on the funding available, type of tenure, etc. As the concept of cohousing is new in the UAE, starting with a small-scale community as a prototype (around 12–15 units in different sizes) is wise.

3.2.2 Cultural and social considerations

The focus group argued that the cultural and social aspects are crucial to consider in the future cohousing in the UAE. The professionals from the UAE highlighted the importance of privacy, which should be maximized both in the units and in between units. In shared facilities, minimal privacy can facilitate social contacts between residents. Private terraces and balconies should not face each other, and visual contact between the common facilities is recommended. In contrast, exposing the private unit entrances is not recommended. On the other hand, the professionals from Sweden emphasized facilitating new experiences for the residents in the cohousing. One significant experience is the concept of sharing, where the residents can share different stuff such as old electrical equipment and grass-cutting machines. It is also essential to share cooking and meals to facilitate social coherence.

3.2.3 Urban design considerations

The professionals from both countries (Sweden and the UAE) underlined that the aspect of urban design is essential to be considered in the future cohousing in the UAE, including 1) providing high-quality urban design to attract the residents to spend time outdoors. It is recommended to consider different materials, colors, and different landscape solutions. It is also recommended to consider an urban farming approach in outdoor spaces where residents can work together to foster social bonds and produce local food, 2) enhancing thermal comfort in outdoor spaces to let people stay for longer periods and use the spaces at different times of the day in different seasons, even in the worst periods, and 3) maximizing the shade using different landscape elements. Trees should have wide canopies, allowing more shade, and better to be evergreen to provide shade all over the year. Outdoor spaces should also facilitate natural ventilation to reduce the amount of dust and the level of heat stress.

3.3 Quality Function Deployment (QFD)

The inter-relationship matrix between resident requirements or VOC and design requirements to develop future cohousing in the UAE is shown in Figure 7. The figure illustrates that aspects such as gaining new experiences, the types of common functions in the house, cultural and social aspects, privacy, innovative design, and outdoor thermal comfort have the highest priorities when developing cohousing in the UAE (Figure 7). On the contrary, other aspects, such as the number of units, typology, and unit layout, have the lowest priorities among the aspects studied (Figure 7).

4 Discussion

Table 2 presents the proposed cohousing design guidelines categorized under their respective significant criteria. The guidelines are ranked according to QFD's technical importance rating derived from 1) semi-structured interviews, which represent VOC, and 2) focus group discussion, which represents the professional viewpoint. Consequently, the proposed design guidelines are suggested for the cohousing indoor and outdoor environments and presented according to their priorities in the QFD model.

The results of this study highlight the importance of common facilities in future UAE cohousing to provide new experiences and foster, for example, social contact, cohesion, and solidarity (see Table 2; Section 3.2). This agrees with other studies showing that the cohousing lifestyle can significantly improve residents' quality of life by enhancing personal autonomy, social support, and solidarity (Labit, 2015; Glass, 2020; Monton et al., 2022). The positive social atmosphere in future cohousing in the UAE can also lead to a better environment, meaning that a cohesive sociality can induce a particular commitment to the surrounding local environment, which, if nurtured, can possibly be extended into broader environmentalism. This goes in coherence with other studies arguing that the supportive social setting often associated with a "sense of community" can contribute to the effective application of pro-environmental attitudes, and the supportive community-based social relations, on the other hand, can engender a sense of belonging and allegiance to one's locale (Meltzer, 2000). In this context, cohousing can induce individuals to engage in environmentally friendly behaviors, such as using a bicycle instead of driving a private vehicle and supporting an individual's commitment to more sustainable practices.

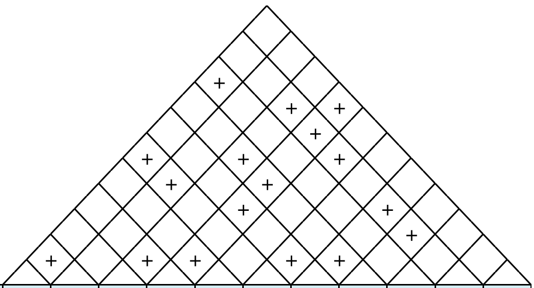
To produce adequate cohousing, the results shed light on the fact that it is vital to design the common facilities in harmony with the local community's culture and sociality, meaning that

QFD: House of Quality
Project:
Revision:
Date:

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



Row #	Weight Chart	Relative Weight	Customer Importance	Maximum Relationship	Customer Requirements (Explicit and Implicit) / Functional Requirements	1 Functions	2 Cultural and Social Aspects	3 Innovative design	4 Urban design	5 Safety	6 Privacy	7 Typology and unit layout	8 Outdoor thermal comfort	9 New experiences	10 Landscape solutions	11 Number of units
					Direction of Improvement											
1		10%	4	9	Bringing back the sense of the old Fareej (traditional housing)	●	●	●	○	●	●	▽	●	●	○	○
2		10%	4	9	Sharing daily life facilities	●	●	○	○	●	●	●	●	●	●	○
3		10%	4	9	Adapting new habits	●	●	▽	▽	●	●	○	○	●	○	●
4		10%	4	9	Preserving and enhancing social values	○	●	●	○	○	●	▽		●		
5		13%	5	9	Sustainable building	○		●	○			●	●	○	●	○
6		10%	4	9	Protection from weather in outdoor space	▽	○	●	●	●	○		●	○	●	
7		8%	3	9	Inviting guests to community Majlis	●	○	▽			●	●		●		●
8		8%	3	9	Knowing neighbors	●	●	○	●		●	▽		▽		○
9		10%	4	9	Kids going back to the urban space	●	○	●	●	●	○		●	●	●	
10		13%	5	3	Time spent on social media	○	▽	▽	○				○	○	○	

	1	2	3	4	5	6	7	8	9	10	11
Target	Co-living, common facilities and local functions	Separate common facilities from private units	Smart and sustainable design	Quality of outdoor spaces	Safe playgrounds with full accessibilty for all	Visual contact : 0% near private spaces to 100% in the common spaces	Attached and detached building geometries	Shading and ventilation	the common facilities are a core to foster social cohesion and solidarity	Trees with wide canopies	Small scale community
Max Relationship	9	9	9	9	9	9	9	9	9	9	9
Technical Importance Rating	610	522.5	555	422.5	480	555	327.5	540	630	480	277.5
Relative Weight	11%	10%	10%	8%	9%	10%	6%	10%	12%	9%	5%
Weight Chart											

FIGURE 7
Matrix of Quality Function Deployment.

the design needs to meet the local needs of future residents (see Section 3.2.1). In order to do this, the participation of future residents in the design process can provide answers to questions about what types of common facilities fit the local and cultural needs of the residents. This agrees well with previous studies that argued that participation started from the involvement of future residents in designing the architectural layout of their community (Durrett, 2010; Bunker et al., 2011). By involving future residents in the design process, the number of residential units in the cohousing can be decided. In addition, the typology and unit layout can also be collectively discussed. This, in turn, will enhance the social aspect among residents. Moreover, the involvement of residents in decision-making (in addition to designing the physical layout) fosters social relationships and

TABLE 2 Proposed cohousing design guidelines.

	Theme	Design guidelines	Technical importance rating
Indoor environment	New experiences	Plan the common facilities as core to create new experience and foster social cohesion and solidarity	630
	Functions	Provide common local functions (majlis, praying room, etc.)	610
	Privacy	Consider visual and physical contact: 0% near private spaces to 100% in the common	555
	Innovative design	Apply smart and sustainable solutions, using environmentally integrated design	555
	Cultural and social aspects	Provide clear boundaries between common facilities and private units	523
	Safety	Consider safe playgrounds with full accessibility for all, by applying universal design, especially for elderly and kids	480
	Typology and unit layout	Mix attached and detached building geometries for different types of people, tenures, etc.	328
	Number of units	Design for a small-scale community (12–15 units in different sizes)	278
Outdoor environment	Outdoor thermal comfort	Maximize shading and natural ventilation in outdoor spaces	540
	Landscape solutions	Plant evergreen trees with wide canopies	480
	Urban design	Consider high-quality design in outdoor spaces to facilitate common activities outdoors	423

social capital (Williams, 2005). This study also highlighted the need to identify a clear line between private and public spaces in the future cohousing in the UAE. This agrees well with previous studies such as Gerards et al. (2015) and Sanooff (2008), who argued that the right balance between privacy and community could only be derived from a participatory design process.

This study confirms that privacy has an impact on the architectural design in the society of the UAE (see Table 2). In this context, the study suggests having a clear division of hierarchy varied from 0% privacy in the common facilities to 100% privacy in the private housing units (see Section 3.2.1). Other studies also highlighted the role of privacy in the cohousing design. Vestbro (2010) indicated that a person needs privacy in co-housing, and architects must, therefore, design semi-private zones where one can sit and talk and look without being 100% sociable all the time. Common spaces with zero privacy should, thus, be easy to enter where the visual connection is also essential, i.e., if a resident can see what is happening without entering the space, he/she can choose to enter or pass by (Vestbro, 2010).

In future cohousing in the UAE, the study shows that it is vital to apply smart building solutions to achieve sustainable building (see Table 2). This agrees with other studies that recommend applying various sustainable technologies such as biomass and solar energy and other solutions that promote energy efficiency (Zurek, 2021). Although the latest technology and smart devices and their maintenance are expensive, the building design can integrate the lifestyle of the residents for more efficient use of these innovative technologies. Sustainable building technologies, smart solutions, and housing design factors could contribute—together with the social commitment of the house—to achieve a low-carbon, even zero-carbon lifestyle. This includes waste sorting, using less heat and hot water, and growing plants and vegetables. Other studies argued that the design of cohousing needs to strike a balance between environmentally friendly technologies and what is acceptable and cost-effective to residents (Marckmann et al., 2012).

This study highlighted that the design of future cohousing in the UAE needs to consider a high level of safety and accessibility for outdoor and outdoor spaces. Regarding the indoor environment, all common and private facilities must be accessible to all ages, especially kids and the elderly (see Table 2). This goes in line with previous studies, which showed that collective housing for the elderly should be designed for all times (Kähler, 2010). If all facilities of the building are accessible for the elderly, it indicates that the building, by default, is accessible for families with children and single households (Vestbro, 2010). In this sense, the building supports the concept of universal design or design for all ages (see Section 3.2.1). This agrees with other studies, indicating the importance of universal design in all housing projects (Mace, 1988; Jones, 2014). In addition to the requirements of safety and accessibility in cohousing, the study also sheds light on the importance of designing attractive facilities for kids and teenagers, as some cohousing projects have designed adequate outdoor playgrounds for kids; however, teenagers are easily forgotten in the design (Vestbro, 2010).

This study indicated that the role of the outdoor environment in future cohousing of the UAE is essential, as many everyday activities can be organized outdoors (see Table 2). Moreover, the findings show that the quality of the urban design can foster social contact among the residents. Therefore, the design of outdoor spaces needs to facilitate adequate shading and proper natural ventilation to fit with the UAE's warm–humid climate and enhance thermal comfort and reduce heat stress outdoors (see Section 3.2.3). This agrees with other studies, which showed that collective housing should have lovely, peaceful, sheltered outdoor spaces, with covering either around or in the middle of the building, which can offer protection against wind, rain, and snow (Kähler, 2010). In the same context, innovative landscape solutions are recommended to be applied. One of the landscape strategies is to consider evergreen trees with wide canopies to maximize the shading in outdoor spaces. In addition, to facilitate more common activities outdoors, different materials, colors, landscapes, and design elements are recommended to be considered. This agrees with Durrett (2010), who argued that the role of the physical design in the cohousing/eco-villages (indoors and outdoors), including the site design, landscape, and architectural design, is highly important in facilitating a social atmosphere and plays a significant role in directing the behavior of the residents in the house.

5 Conclusion

This study aimed to develop design guidelines for future cohousing in the UAE. Focusing on the pillars of the Estidama program, i.e., social, cultural, economic, and environmental aspects, in addition to the role of architectural design, the proposed guidelines are divided into the indoor environment and outdoor environment.

Regarding the indoor environment, the design of future cohousing in the UAE should focus on the role of common facilities as a tool to enhance the social contact between residents and provide new experiences to foster, for example, cohesion and solidarity. The future design of cohousing in the UAE also needs to provide common local functions such as majlis and praying rooms. Future cohousing in the UAE should also pay attention to the privacy of the residents as it reflects the local society's culture, religion, etc. Therefore, a clear boundary to define the private spaces from the common spaces is crucial in the design. In addition, the design layout needs to consider different levels of visual and physical contact between different facilities in the cohousing. In this context, privacy needs to be well-identified and varies between 0% in the common facilities and 100% near and inside private units. Moreover, how "privacy" is seen in the local culture is another requirement for good design, meaning that good design can guide people to the right places without reading signposts or info boards. In addition, the design of the cohousing needs to apply smart and sustainable solutions using environmentally integrated design. The design also needs to consider safe playgrounds with full accessibility for all types of people by applying universal design, especially for the elderly and kids. As for the typology, the cohousing design needs to mix attached and detached building geometries, considering different types of people, tenures, sizes, etc. Regarding the scale, it is better to start with a limited number of units for small-scale communities (12–15 units in different sizes) when developing cohousing in the UAE.

Regarding the outdoor environment, the design of cohousing in the UAE needs to contribute to a better thermal environment by maximizing the shade and natural ventilation in the outdoor spaces, enhancing the level of thermal comfort, and decreasing the heat stress outdoors. The cohousing design also needs to apply innovative landscape solutions and tree selection, for example, considering evergreen trees with wide canopies to maximize shade. One of the important guidelines for the outdoor environment is to consider high-quality design in outdoor spaces to facilitate common activities outdoors. In this context, using different materials, colors, landscapes, and design elements is recommended to be applied in future outdoor spaces of cohousing in the UAE.

Data availability statement

The datasets presented in this article are not readily available because it contains sensitive information. Requests to access the datasets should be directed to the corresponding author.

Author contributions

MY is the main author and was mainly responsible for finalizing the article and contributed to data collection, contextual analysis, and theoretical framework. MY, EM, SD, AO, and AM contributed to the the conception and design of the study. MY, YA, KA, and SY have contributed to data collection and analysis and composed the drafts of the manuscript. MY, EM, SD, AO, and AM have also contributed to the manuscript revision and read and approved the submitted version. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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