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Regenerating traditional Omani souqs: Climate-responsive biophilic design and thermal performance simulation

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Abstract
Climate change and urban heat island effects, as well as the loss of vernacular passive cooling features, are causing accelerated thermal degradation in the traditional souqs of the Arabian Peninsula. One such example is the Nizwa Souq, a heritage marketplace, nationally designated, located near the UNESCO-recognized Nizwa Fort, Oman, operating under extreme Universal Thermal Climate Index (UTCI) conditions typical of hot desert (BWh Köppen-Geiger) climates. This study investigates the thermal comfort enhancement achievable through biophilic design interventions, namely native shade trees, water features inspired by falaj, and high albedo ground surfaces, which can enhance thermal comfort through multi-parameter microclimate simulation, utilizing the Infrared.city platform and weather data from TMYx 2009–2023 (OMNDANizwa. 412550_TMYx). Two scenarios were compared: Scenario A (Existing Baseline) and Scenario B (Biophilic Intervention). Seven different types of complementary simulations were used: UTCI, Thermal Comfort Statistics, Direct Sun Hours, Sky View Factor, Solar Radiation, Wind Speed, and Lawson Pedestrian Wind Comfort Criteria. Findings demonstrate a substantial improvement in outdoor livability during peak summer conditions (July, 10:00–14:00), alongside significant improvements in solar interception, sky visibility reduction, and thermal distribution uniformity, collectively indicating that biophilic interventions can meaningfully shift the thermal profile of heritage desert open spaces. A seasonal trade-off was found: tree canopies provide critical summer shading, slightly decrease solar warming during the winter, highlighting the need to choose seasonally adaptive, climate-native species. The study provides evidence-based design guidelines for climate-sensitive heritage regeneration in the Arabian Peninsula and contributes a replicable methodology for practitioners working within conservation-constrained settings.

Keywords: Outdoor thermal comfort, Heritage marketplace, Biophilic design, Traditional urban spaces, Hot desert climate, Nizwa Souq, Microclimate simulation, Sky view factor, UTCI

1. Introduction

Urban heat stress is increasing worldwide, and the arid regions of the Middle East face some of the most extreme thermal conditions on Earth. Research demonstrated that urban overheating and heat island effects in desert cities have increased, leading to synergistic effects on energy use, human health, and social vulnerability [1]. The Arabian Peninsula, with its high solar radiation, low precipitation, and high ambient temperatures that often exceed 45°C, poses an exceptionally difficult environment for maintaining outdoor thermal comfort in open public spaces [2]. Traditional souqs of the Arabian Peninsula are culturally irreplaceable community spaces serving as centers of trade, social life, and cultural identity [3]. These historic marketplaces have served for centuries as pivotal nodes in the urban fabric, embodying local architectural intelligence and socio-economic heritage [4]. Traditional souq's spatial and functional importance was documented by Abid in Oman, and in Qatar, Mazzetto, Furlan, and Hoblos explored the potential of adaptive reuse of traditional souqs in the context of transit-oriented development [5]. Significantly, the traditional souq typologies featured advanced passive cooling elements such as narrow covered lanes (arcades/saqifas), courtyard designs, thick-walled buildings with thermal mass, wind-towers (barjeel), and evaporative cooling using the qanat, all vernacular design responses that reduced extreme radiative loads [6]. However, owing to climate change, the growth of urban heat islands and the slow disappearance of these traditional passive cooling elements as a result of modernization and uncontrolled additions, these heritage spaces are becoming increasingly thermally hostile [7].

Nizwa Souq exemplifies this critical challenge. The souq is located in the historic city of Nizwa, Ad Dakhiliyah Governorate of Oman (22.9332ºN, 57.5310ºE), Adjacent to the 17th-century Nizwa Fort, one of the largest forts on the Arabian Peninsula, and the Grand Masjid. It hosts the renowned Al Habta livestock auction, date and silver craft markets, pottery and gold markets, and is a multi-purpose heritage center that represents the cultural identity of the Omani interior. The Venice Charter (1964) and its derivative frameworks, as articulated by Posina and Corti. Impose critical constraints on permissible physical interventions in listed heritage sites, precluding major structural alterations while permitting reversible, nature-based interventions that enhance environmental performance without compromising heritage fabric integrity [8]. Despite their unique cultural value, outdoor thermal comfort in heritage urban settings remains a severely under-researched intersection [9]. Most outdoor thermal comfort research has been conducted by Rezaei and Lopez, who demonstrated only contemporary urban environments, streetscape, and public spaces; very few studies have been done on traditional marketplaces and heritage precincts. In the Arabian context, this gap is very significant because the conservation and regeneration of traditional urban spaces is a national agenda linked to tourism development, cultural sustainability, and community welfare [4]. Biophilic design, the intentional integration of nature and natural processes into the built environment through the use of vegetation, water features, natural materials, and sensory experiences with nature, has been shown to have significant thermal mitigation potential in urban settings [10]. But most importantly, biophilic interventions fit with the principles of heritage conservation; they are reversible, not invasive, and do not affect the structural or architectural character of protected sites [11]. This positions biophilic design as the preferred intervention strategy for thermal improvement of heritage buildings, rather than mechanical cooling or permanent structural alterations that would affect the heritage authenticity [12]. The Infrared.city simulation platform developed by the City Intelligence Lab at the Austrian Institute of Technology (AIT) allows for a quick and evidence-based scenario testing at the urban level by combining computational fluid dynamics, solar radiation modelling, and UTCI calculations in an accessible decision-support environment [13]. By leveraging these advanced simulation tools, researchers can evaluate the synergistic cooling effects of multiple nature-based solutions, which often outperform individual mitigation strategies in reducing ambient temperatures and peak heat intensity [14]. Despite these advances, no prior study has quantified the thermal impact of biophilic design interventions in a traditional Omani souq by using multi-parameter microclimate simulation [15]. This research aims to fill that gap by: (1) developing a thermal comfort baseline for Nizwa Souq based on the UTCI and representative meteorological data; (2) simulating a full biophilic intervention scenario, comprising native shade trees, water features inspired by falaj and reflective ground materials; (3) quantifying thermal improvement across complementary parameters such as UTCI, Sky View Factor, Direct

Sun Hours, Solar Radiation, Thermal Comfort Statistics and Wind Speed (Lawson Criteria); and (4) identifying performance trade-offs between the different seasons to guide species selection and seasonally adaptive design in heritage contexts [16].

1.1. Literature review

1.1.1. Thermal comfort in hot, dry urban environments

The UTCI is the most physiologically complete index for evaluating thermal comfort in the outdoors. The UTCI is based on a complex multi-node human thermoregulation model and four basic environmental parameters: air temperature, wind speed, humidity, and mean radiant temperature, and is developed within the COST Action 730 project. The UTCI, unlike simpler indices like the Physiological Equivalent Temperature (PET) or Wet Bulb Globe Temperature (WBGT), considers dynamic adaptation mechanisms like clothing adjustment behavior and is therefore especially suitable for the outdoor comfort assessment under various climatic conditions [17]. The mathematical foundation of present simulation platforms is the operational derivation procedure, which was established by T. Xu, R. Yao [18].

Thermal stress research in the GCC and wider Middle East has consistently reported UTCI values exceeding human tolerance thresholds for extended periods [19]. The building height to width ratio, street aspect ratio, and other morphological parameters are dominant parameters affecting the thermal performance at the pedestrian level in hot arid regions was shown by Hamanna [1]. Their findings suggest that even modest increases in street canyon enclosure ratios yield measurable UTCI reductions, informing the rationale for examining how vegetation can functionally replicate the sky-obstruction effect of traditional covered souq morphology [20]. A cross-cultural thermal comfort study that showed that cultural adaptation and behavioral thermoregulation can only partially reduce the physiological stress and cannot block the extreme radiative load in Gulf cities if physical environmental modification is not done, this study was conducted by Ratmia [1].

The Sky View Factor (SVF) is one of the most important morphological factors controlling the amount of diffuse and direct radiation received by the ground plane and thus the outdoor thermal comfort. The groundwork for the relationship between SVF and urban energy balance was laid by Gulten and Alhumaidi, and took it one step further by analyzing the urban form and the composition of street canyons using deep learning [21]. High SVF values (close to 1 in open plazas and unobstructed sites) correspond directly to high mean radiant temperatures and UTCI values because the ground plane has the maximum solar irradiance and the least obstruction to the sky [22]. This morphological constraint can be directly applied to the open plaza and market grounds of Nizwa Souq, where there is no cover above, creating conditions similar to a perfectly open terrain. The interdependence of thermal comfort and outcomes of heritage conservation, as preserving a thermally habitable environment in traditional souqs is a precondition for their social functions and economic viability, this was highlighted by Santamoris [23].

1.1.2. Heritage urban spaces and thermal challenges

The traditional typology of the souq in the Arabian Peninsula reflects centuries of environmental design wisdom. The narrow lanes, covered arcades, courtyard design, and thick walls are all examples of advanced passive cooling techniques that have been developed through cultural adaptation to the harsh desert climate. These typological features of Gulf souqs were reported by Manshour and Lehman, who showed that covered streets with limited sky view, deep shade, and stack-effect ventilation can maintain temperatures significantly lower than adjacent open areas [6]. The spatial and functional analyses on two traditional markets, namely Souq Mutrah (Oman) and Souq Waqif (Qatar) was performed by Benlahbib, which have confirmed that the morphology of traditional markets directly influences the usage patterns, comfort, and the intensity of social interaction. [1], [3], [24]. The central paradox of heritage thermal improvement is that conservation frameworks, most notably the Venice Charter (1964) and its derivative frameworks, as theorized by Bakun, have strict limits on what physical interventions can be made on listed heritage sites [25]. The frameworks prevent changes that affect the authenticity of the material, spatial character, or structural integrity of the heritage fabric. Nizwa Souq is located within the buffer zone of the UNESCO-associated Nizwa Fort complex and is subject to conservation requirements [26]. This restriction focuses on interventions that are reversible, natural, and can enhance the environmental performance without compromising the heritage fabric, such as trees, water features, and removable shade structures. In particular, the open plaza, the main pedestrian pathways, and the market ground areas of Nizwa Souq offer the highest potential for the insertion of biophilic layers: these are the most thermally hostile areas and are not conserved by the same structural constraints as the covered souq buildings, and can therefore be targeted for climate-responsive interventions [3]. Furthermore, integrating such interventions aligns with the imperative to revitalize traditional markets as centers of socio-cultural interaction by mitigating the severe thermal stress that currently limits pedestrian engagement in these historical areas [27], [28].

1.1.3. Biophilic thermal mitigation interventions

Urban trees are the most prevalent documented biophilic intervention for thermal mitigation outdoors. The urban trees can lower UTCI by 2-8°C by synergistically reducing direct solar radiation reaching the pedestrian plane by providing canopy cover and by converting sensible heat to latent heat through evapotranspiration was determined by Urrutia [13]. The amount of cooling differs depending on the species; broad canopy deciduous species provide the greatest cooling in the summer and do not block out too much sun in the winter. In hot arid climates, drought-resistant native species such as the Ghaf tree (Prosopis cineraria) and date palm (Phoenix dactylifera) are both climatically adapted and culturally appropriate for souq settings [29]. Furthermore, the integration of such vegetation must be carefully balanced with local shading practices to ensure that visual vistas of heritage monuments are maintained while simultaneously optimizing microclimatic thresholds [30], [31].

Water features offer complementary thermal mitigation in the form of evaporative cooling that can be very effective in hot, dry climates with high vapor pressure deficits. The temperature drops at pedestrian level from pavement watering as a mitigation strategy for urban heat islands, which ranged from 1 to 3°C, was measured by Joshi. The traditional Omani falaj irrigation system, which is a network of open channels bringing water from the mountains, provides a culturally authentic precedent for the integration of water into open urban space [32], [13]. The design of water features that refer to the falaj heritage has two aims: to improve thermal performance and to strengthen the intangible expression of cultural heritage [33]. The thermal stress can be reduced by lowering the surface temperature and decreasing the upward longwave radiation flux from the ground plane by using reflective and high albedo ground surfaces. The radiant surface temperature decreases by up to 15°C when compared to the conventional dark asphalt, which results in measurable reductions in the mean radiant temperature at pedestrian level was shown by Zhou [34]. Synergistic effects of green-blue infrastructure (GBI) combining vegetation, water, and surface treatments are more than the sum of individual measures, as Yang Hu showed in their assessment of thermal stability for urban functional zones [35]. Strategic deployment of green and blue infrastructure facilitates microclimate regulation through complex processes, including evapotranspiration, shading, and the modulation of air movement [36], [37].

1.1.4. Microclimates simulation tools for design assessment

The Infrared.city platform represents a significant advancement in accessible urban microclimate simulation. The City Intelligence Lab of the Austrian Institute of Technology (AIT) has developed a platform that can be used to calculate UTCI, wind velocity, solar exposure, and SVF at an urban scale based on a physics-based simulation that was accelerated with machine learning. The InFraRed intelligent framework for resilient design, and its ability to perform rapid iterative scenario analysis, was shown by Briegel [38]. The machine learning and artificial intelligence methods that enable computational acceleration with preserved physical accuracy [39]. These computational advancements enable architects to evaluate the thermal impact of specific design parameters—such as street geometry, pavement albedo, and landscape elements—with high precision [40]. Typical Meteorological Year (TMYx) weather file inputs provide statistically representative multi-year climate data instead of the anomalous data from a single year. Verified TMYx-based simulation for urban shape optimization, confirming that TMYx inputs provide good comfort prediction for design decision making [41]. Comparative scenario-based simulation, where a baseline condition is systematically compared with one or more intervention scenarios with the same environmental inputs, such models serve as vital instruments for bioclimatic design, allowing researchers to accurately quantify microclimatic conditions and validate the effectiveness of heat mitigation strategies [42]. The intervention scenarios using the same environmental conditions as inputs have become the standard methodology for design performance evaluation, and this methodology is adopted as the framework for this study, which was compared by Pasandi. Computational simulations allow for the analysis of multiple design scenarios to determine their impact on human thermal comfort [43].

1.2. Study area and climate context

1.2.1. The site description and heritage value of Nizwa Souq

The study area encompasses Nizwa Souq and its immediate urban environment as seen in Fig. 1, along Al Thaqafa Road, in the historic city of Nizwa, Oman (22.9332°N, 57.5310°E). The site boundary covers 262,144.72 m² with a perimeter of 2,048 m. The souq has excellent heritage value as a nationally designated souq, next to the largest fort on the Arabian Peninsula, Nizwa Fort, which was built in the 17th century and is situated within Oman's tentative UNESCO World Heritage site framework, and the Grand Masjid of Nizwa. The designation of the souq as a national heritage site under Omani law (protected heritage site under the Ministry of Heritage and Tourism) and the designation of the fort complex and its buffer zone (which includes the souq) by UNESCO are two different designations. There are separate commercial areas, including the Eastern Al Sansra market, silver and craft market, pottery market, gold market, dates market, and the livestock market with the world-famous Al Habta Friday auction. The site has a mixed-use, low to medium density urban morphology with covered and open spaces. The covered areas are traditionally designed with narrow lanes, lacking any sky view and deep thermal shade, in line with the passive cooling intelligence of the Arabian souq typology. On the other hand, most of the open areas, such as the central plaza area between the souq and Nizwa fort, main pedestrian circulation pathways, and the livestock auction ground, are open with no shading and direct exposure to the solar radiation during the day. This morphological heterogeneity results in very high thermal gradients between shaded and exposed areas, where the exposed areas offer the highest thermal stress and thus the greatest potential for biophilic design intervention. The site, as seen in Fig.1, is a unique meeting place of heritage commercial value, cultural identity, and environmental challenge.

Figure 1. Location map of Nizwa Souq: Regional level (Oman), City level (Nizwa, Ad Dakhiliyah Governorate), and Site boundary (262,144.72 m²)

Source: Author adapted from satellite imagery

The site has mixed-use urban morphology with covered and open spaces, as documented in the site survey in March 2026 in Fig. 2. The traditional covered lanes have limited sky view and strong thermal shade, and the open spaces (such as the central plaza between the souq and Nizwa Fort, the main pedestrian routes, and the ground for the livestock market) are mostly without shade. This morphological heterogeneity generates the extreme thermal gradients, open spaces are the areas with maximum thermal stress and the biggest potential for biophilic design intervention.

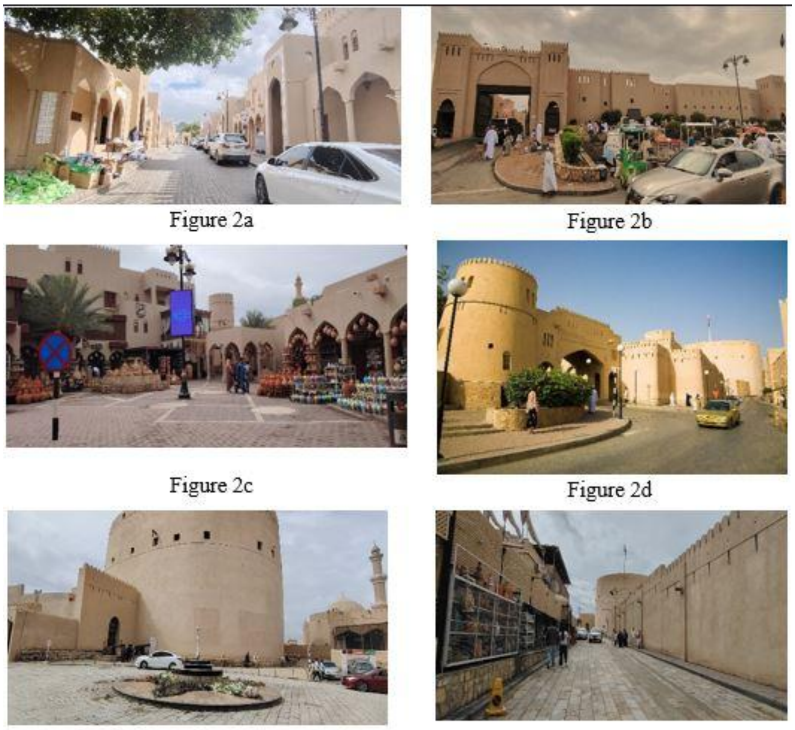

Figure 2a Figure 2b

Figure 2c Figure 2d

Figure 2e Figure 2f

Figure 2. Photographic survey of the precinct of Nizwa Souq (March 2026 field visit)

Figure 2 shows (a) Pedestrian avenue along commercial facade with no overhead shading; (b) Traditional arched gateway with open forecourt; (c) Open-air craft market zone with no canopy shade; (d) Nizwa Fort circular tower and thermally exposed plaza; (e) Fort entrance plaza with minimal vegetation; (f) Pedestrian Street with canyon-like section and no canopy shade.

Source: Author, March 2026.

1.2.2. Climate analysis

According to the Köppen-Geiger climate system, Nizwa falls under BWh (Hot Desert Climate), which is characterized by extreme aridity, high solar radiation, and high diurnal temperature range. The weather data presented in Fig. 3 for the TMYx 2009 to 2023 (OMNDANizwa. 412550TMYx) shows a mean annual temperature of 28.86°C with the maximum temperature of 47.8°C in the month of August and the minimum temperature of 7.8°C in the month of February. The mean annual relative humidity of 37.18% in Fig. 3 indicates that the atmosphere is mostly dry, which would allow for the greatest evaporative cooling potential of water-based interventions. The climate is completely cooling dominated with 3,638 cooling degree days (CDD) (base 18°C) and 0 heating degree days (HDD). The UTCI thermal stress ranges from 7.9°C (no thermal stress) in winter mornings to 55.6°C (extreme heat stress, UTCI > 46°C) in summer afternoons, with an annual average of 31.8°C. Severe to extreme heat stress (UTCI > 38°C) is the predominant condition for the months April to October, rendering outdoor activity thermally hazardous during 10:00–18:00, effectively making the external environment inhospitable for about half of the calendar year. Monthly Horizontal Infrared Radiation is the largest source of longwave radiation that affects outdoor thermal stress, with peaks in July–August at ~445 Wh/m2 monthly average. The annual cloud cover is below 20%, which means that there is high solar loading on the ground and building surfaces during the long summer season. From the wind rose analysis of the TMYx data, it is found that the prevailing wind direction is westerly.

Together, the climate analysis in Fig. 3 shows that Nizwa Souq is located in one of the hottest outdoor climates in the world, with both shortwave solar radiation and longwave infrared radiation responsible for the high UTCI values during the long summer season. This highlights the need for thermal mitigation measures and the fact that any improvement in the outdoor comfort conditions is of great practical value for the vitality of heritage, social function, and commercial activity.

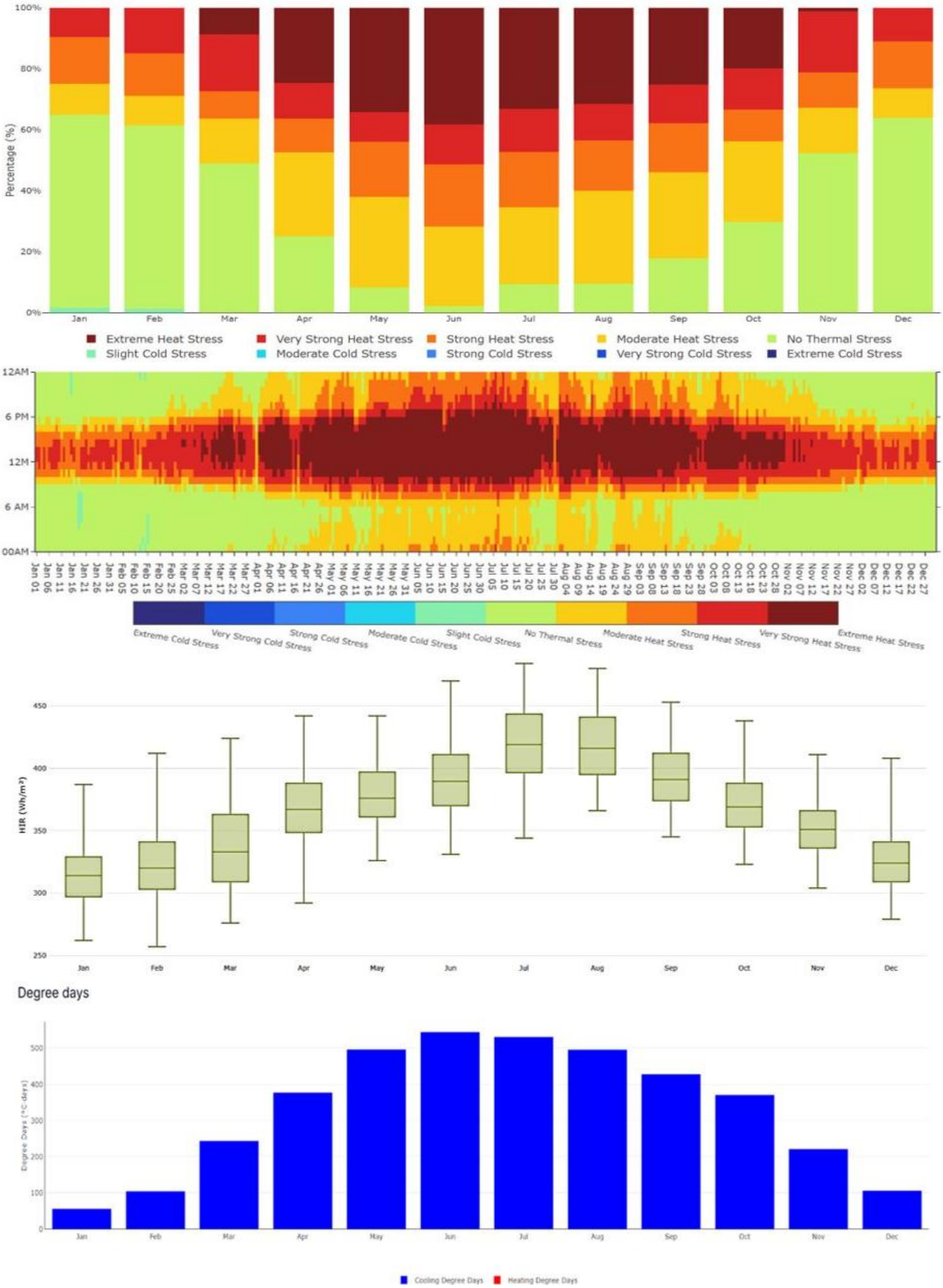

Figure 3. Climate analysis for TMYx 2009-2023 Nizwa, Oman. (a) Hourly UTCI heatmap – annual thermal stress distribution; (b) Monthly UTCI thermal stress category breakdown; (c) Infrared horizontal radiation monthly boxplot (Wh/m²); (d) Cooling and heating degree-days histogram

Source: Author via Infrared.city simulation

2. Methodology

2.1. Simulation platform

Microclimate simulation was conducted using the Infrared.city platform (version 2.0) developed by the City Intelligence Lab of the Austrian Institute of Technology [44]. The platform brings together computational fluid dynamics, solar radiation modelling, SVF computation, and UTCI calculation in a single web-based platform, allowing for quick iterative scenario analysis at the urban level. In contrast to the use of CFD-only workflows that are specific to particular software (e.g., Rhino/Grasshopper, Ladybug Tools), Infrared.city presents an easy-to-use and evidence-based microclimate assessment for design professionals who do not have a high level of computational skills [45].

Furthermore, this tool facilitates the assessment of complex urban dynamics, such as the spatial distribution of airflow and the impact of varied urban densities on pedestrian-level thermal comfort metrics [46]. The following simulation in Fig.4 assumptions and limitations are explicitly acknowledged: (1) Calculations of the UTCI are based on the assumption of standard metabolic activity (walking, 1.1 met) and adaptive clothing adjustment; (2) building geometry is derived from available 3D city model data, with a limit of the accuracy of the building height data in the available urban datasets; (3) wind modelling is based on steady-state CFD assumptions and TMYx dominant wind conditions; (4) no field validation data was collected during the site visit (only photographic survey was conducted) in March 2026, which is a recognized limitation in simulation-based studies and must be resolved in future by deploying portable weather stations.

Weather data were sourced from the TMYx 2009-2023 file for Nizwa (OMNDANizwa. 412550_TMYx.2009-2023), a statistically representative TMY file, which is 15 years of observed meteorological data. Building footprints, heights, and surrounding context buildings that had an impact on wind flow and shading patterns were included in the 3D site model across the study area, as demonstrated in Figure 4.

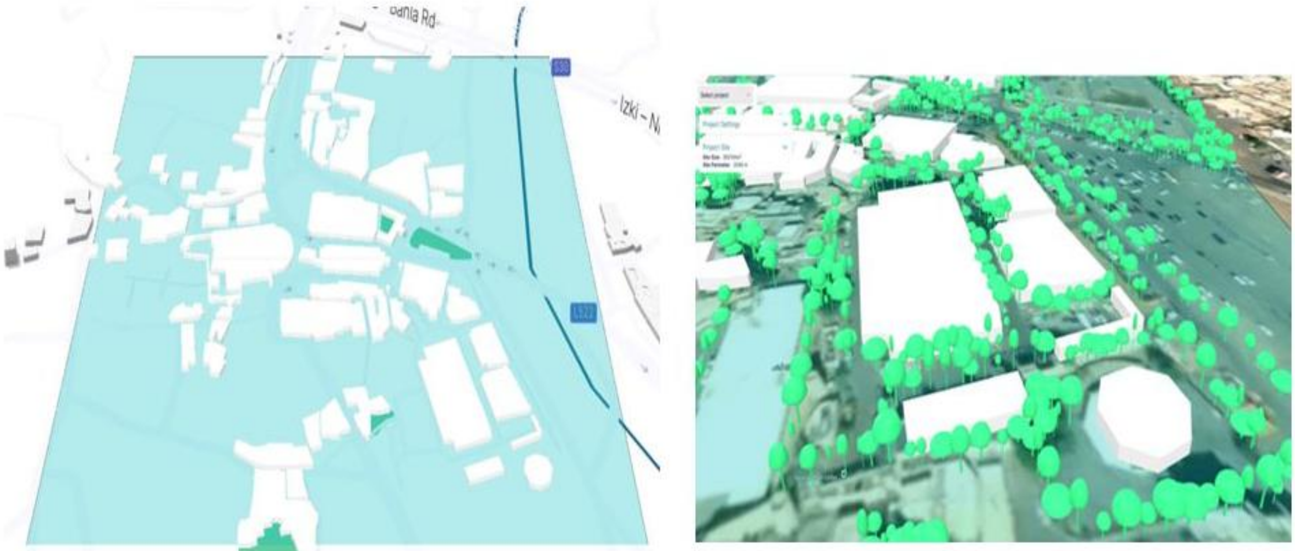

Figure 4a. Scenario A Figure 4b. Scenario B

Figure 4. Data inputs include the TMYx 2009–2023 weather file and a 3D urban model of Nizwa Souq

Source: Author via Infrared.city simulation

Two scenarios were tested (shown in Figure 4): Baseline (Scenario A) and Biophilic Intervention (Scenario B). Seven simulation types were conducted: UTCI, thermal comfort statistics, direct sun hours, SVF, solar radiation, wind speed, and Lawson criteria. Results were evaluated through performance metrics and indices, followed by comparative analysis.

2.2. Simulation parameters

Seven complementary simulation types were performed for each of the scenarios, resulting in a multi-parameter thermal analysis, including physiological comfort, solar exposure, radiative geometry, and wind conditions.

2.2.1. Thermal comfort index (UTCI)

Physiologically referenced equivalent temperature (°C) that combines air temperature, wind speed, humidity, and mean radiant temperature. UTCI < 9°C = no stress; 9–26°C = no/moderate; 26–32°C = moderate; 32–38°C = strong; 38–46°C = very strong; >46°C = extreme heat stress.

2.2.2. Thermal comfort statistics

Temporal comfort distribution indicators such as Range Based Comfort Score (higher = better temporal spread of comfortable conditions), Average Condition Comfort (higher % = more comfortable hours), and Comfort Opportunity Index (COI; lower values indicate better thermal load distribution and greater proportion of thermally accessible time).

2.2.3. Direct sun hours

Solar exposure patterns measured by SAI Weighted Score (higher = more solar interception effectiveness), Sun Exposure Uniformity (lower = more heterogeneous shade distribution), and Coefficient of Variation (higher = more variable, user-beneficial shade patchwork).

2.2.4. SVF

Radiative geometry indicators such as Mean Sky Visibility Index (lower = better sky obstruction by canopies), Sky Access Uniformity (the lower, the more varied the sky exposure), and High Sky Openness Coverage (the lower, the reduced open-sky area).

2.2.5. Solar radiation

Total solar energy load accumulated, Mean Solar Performance Index (lower = better), Solar Distribution Uniformity (lower = more heterogeneous radiation landscape), and Irradiance Potential Index (lower = less total irradiance load).

2.2.6. Wind speed

Defines Ventilated Area (%), Comfort Wind Area (%), and Safe Wind Area (%), creating wind comfort and safety conditions throughout the site.

2.2.7. Pedestrian wind comfort (lawson criteria)

Defines wind conditions with respect to pedestrian activity with the Lawson Comfort Criteria framework, and categorizes wind conditions as acceptable or unacceptable for sitting, standing, walking, and retail/business activities.

2.3. Scenario design

Two scenarios were modelled and simulated with the same environmental inputs and computation parameters.

2.3.1. Scenario A baseline

As shown in Fig 4a. This was a simulation of the existing state of Nizwa Souq, which included current urban morphology without any design interventions. The physical fabric reflects the existing condition of the site; the majority of the open spaces are hard-paved (cobblestone and concrete), there is very little tree coverage in open plazas and pedestrian routes (less than 5% of the total open ground area), no water bodies, and the existing mix of covered souq lanes and exposed open market grounds. The heights of the buildings vary from 4 to 12 m throughout the site. This situation is what the thermal conditions are when the effectiveness of interventions is measured against.

2.3.2. Scenario B biophilic intervention

As shown in Fig 4b. A holistic biophilic intervention was designed based on the morphological analysis of thermal vulnerability zones, cultural precedent, and conservation limitations. The placement decisions were made based on the highest SVF areas (open plaza, main pedestrian routes, and market grounds) identified by the results of the Scenario A simulation, to maximize the effectiveness of the interventions without changing the covered heritage souq buildings. Three complementary types of intervention were used and analyzed in the table.1 below. Native shade trees were planted along pedestrian pathways and in open plaza areas (1) Date palm (Phoenix dactylifera) and (2) Ghaf tree (Prosopis cineraria). Tree specification: 6-8 m height, 3-5 m canopy radius, deciduous or semi-deciduous habit to create seasonality in canopy. Species were selected based on cultural authenticity, extreme drought resistance (no supplementary irrigation needed at maturity), and the legacy of biodiversity in the Omani landscape. The matrix below in Table 1 summarizes key species attributes.

Table 1. Tree species matrix — physical and functional attributes (Scenario B)

Attribute	Date Palm (Phoenix dactylifera)	Ghaf Tree (Prosopis cineraria)
Height at maturity	8–15 m	6–10 m
Canopy radius	3–4 m	4–6 m
Leaf Area Index (LAI)	2.5–3.0	3.0–3.5
Canopy type	Semi-deciduous (frond density seasonally variable)	Deciduous (winter leaf-drop)
Water demand	Low (drought-tolerant)	Very low (hyper arid adapted)
Cultural significance	National symbol, commercial crop, Omani heritage	National tree of UAE/Oman, intangible heritage
Summer shade effectiveness	Moderate (vertical frond structure)	High (horizontal spreading canopy)
Winter sun penetration	Good (reduced frond density)	Excellent (deciduous, full leaf-drop)

2.3.3. Falaj-inspired water features

Linear and point water channels were identified in central open courtyard locations and along pedestrian routes, mimicking the geometry and cultural language of the traditional Omani falaj irrigation system, a UNESCO-inscribed intangible heritage element. Water feature dimensions: channel width 0.3-0.5 m, channel depth 0.2 m, recirculating pump systems to reduce water use in this water-scarce environment. In summer, the operation will be optimized for maximum afternoon periods (10:00 – 16:00).

2.3.4. High albedo reflective ground surfaces

Existing dark hardscape surfaces (cobblestone and dark concrete) were replaced with light color reflective ground materials (pale limestone aggregate, albedo ≈ 0.55–0.65) throughout the open plaza and market ground areas to reduce surface temperatures and attenuate upward longwave radiation from the ground plane.

2.4. Comparison framework

Peak summer (July) was identified as the key comparison period, and the 10:00–14:00 time window was considered as the maximum solar stress period. Secondary seasonal comparisons were made for spring (March–June) and winter (January, 10:00–14:00) to assess performance differences and compromises between seasons. For both scenarios, percentage change and absolute point differences were determined for all seven types of simulations.

3. Results

3.1. Baseline thermal conditions (Scenario A)

The baseline simulation shows that the Nizwa Souq is indeed an extreme thermal stress environment. The site-wide annual mean UTCI of 31.8°C hides the fact that there is a large seasonal variability with summer afternoon peak UTCI of 55.6°C, which falls in the extreme heat stress category (UTCI > 46°C), where the risk of human thermoregulatory breakdown and heat-stroke is substantially increased. The accumulated 3,638 cooling degree-days (base 18°C) and no heating degree-days indicate that the thermal regime was completely cooling-dominated. The Mean Sky Visibility Index of 95.50% in the open spaces is a key diagnostic result: it is close to the theoretical maximum of 100%, which means that the open plaza, market grounds, and pedestrian routes of Nizwa Souq are actually indistinguishable from flat open terrain with no sky obstruction, the morphological condition of maximum solar and diffuse sky radiation exposure. These open spaces offer almost no self-shading, whereas the adjacent covered souq lanes are extremely clever in terms of passive cooling, with the existing urban fabric. The Livability Gradient Index (LGI) measures the proportion of the site with UTCI< 32°C (higher = better), which is only 1.14% for the open site area, indicating that less than 2% of the open site area is thermally livable at peak summer stress.

3.2. Thermal comfort index (UTCI)

Table 2 presents UTCI indicator comparisons in the peak summer months (July, 10:00-14:00). Metric definitions: LGI = proportion of site area with UTCI temperature below 32°C (higher = more livable); Spatial Variance Reduction Index = reduction in spatial variance of UTCI temperature (lower = more uniform, lower values indicate less heterogeneity which may be good or bad depending on context); Temperature Uniformity Index = spatial heterogeneity of thermal conditions (higher = greater diversity of microzones, beneficial for user thermal choice).

Table 2. UTCI thermal comfort index comparison, July peak (10:00–14:00)

Metric	Baseline (A)	Intervention (B)	Change
Spatial Variance Reduction Index	61.37%	55.75%	−5.62 pts
LGI (July 10–14h) [higher = better]	1.14%	4.01%	+251.7%
Temperature Uniformity Index [higher = more diverse microzones	0.97%	3.01%	+210.3%

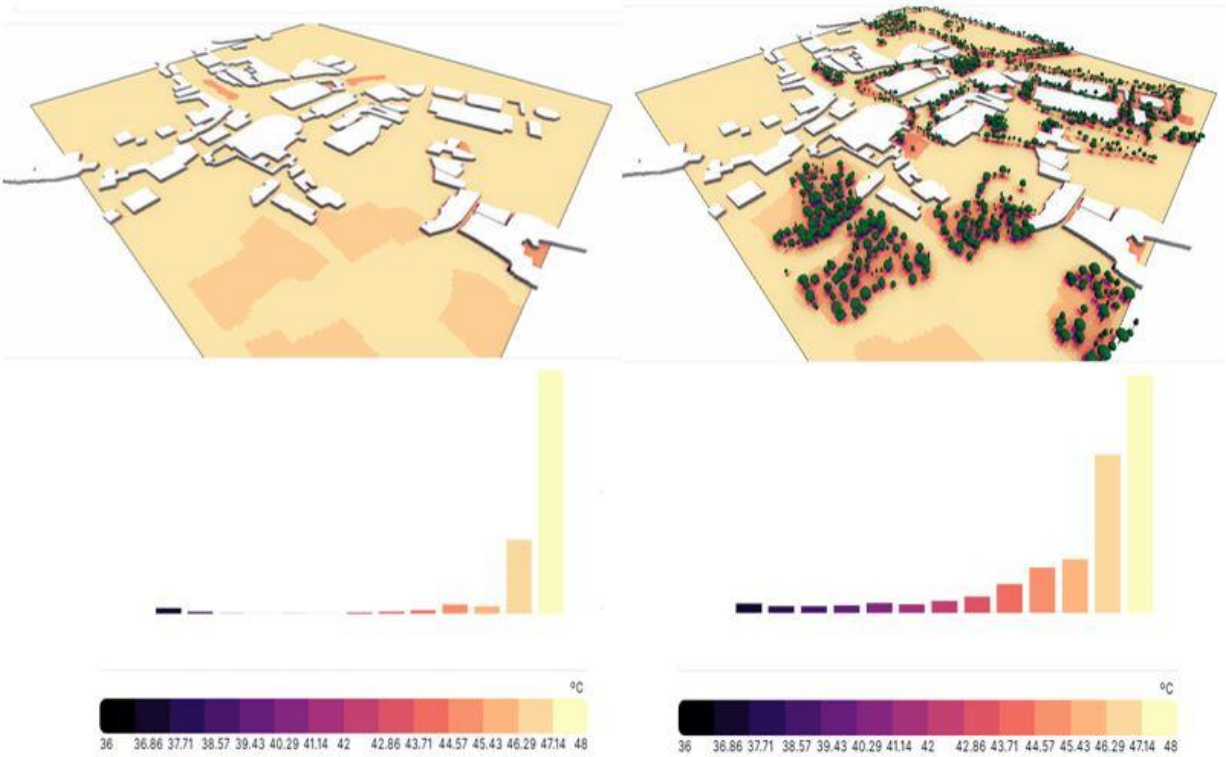

Figure 5. UTCI comparison maps, July peak (10:00–14:00)

Figure 5 shows: Left: Scenario A (Baseline), almost uniform extreme heat stress for all open spaces. Right: Scenario B (Biophilic Intervention), localized cool zones under the placement of tree canopy in the open plaza and pedestrian routes. Color scale: 36–48°C UTCI.
Source: Author via Infrared.city simulation.

The LGI was calculated as the percentage of the site area with livable thermal conditions (UTCI < 32°C), and this increased by 251.7% from 1.14% under baseline conditions to 4.01% with biophilic interventions is demonstrated in Fig. 5. While the absolute values are still low, given the harsh summer climate in Nizwa, the relative improvement is significant; over three times the thermally habitable site fraction for the most extreme thermal hours represents a tangible increase in the amount of shaded space available for vendors, visitors, and residents. The Temperature Uniformity Index increased by 210.3%, showing that the intervention has produced a non-uniform thermal environment with cooler micro zones, which provide more thermal choice for the occupants as indicated in Fig. 5.

3.3. Thermal comfort statistics

Thermal comfort statistics for the spring season (March-June) are given in Table 3. The metric definitions are as follows: Range Based Comfort Score = absolute value of the breadth of thermally comfortable conditions (lower = better, improving trend = better); Average Condition Comfort = mean percentage of thermally comfortable hours across the site (higher = better); Comfort Opportunity Index (COI) = composite indicator of the percentage of time the site is above thermally comfortable ranges (lower = better thermal performance, more hours thermally accessible).

Table 3. Thermal comfort statistics comparison, Spring (March–June)

Metric	Baseline (A)	Intervention (B)	Change
Range Based Comfort Score [lower trend = better]	15.25%	12.88%	−2.37 pts
Average Condition Comfort [higher = better]	26.12%	23.83%	−2.29 pts
Comfort Opportunity Index [lower = better]	21.99%	17.38%	−4.61 pts

The COI improved by 4.61 percentage points (from 21.99 to 17.38). Lower values indicate better performance. This improvement suggests an increase in the window of thermally comfortable time outdoors during the transition seasons of spring and has practical implications for the marketplace to increase its commercial operating time.

3.4. Direct sun hours

Table 4 presents the comparative results of direct sun hours in July, highlighting the differences between the baseline scenario (A) and the intervention scenario (B).

Table 4. Direct sun hours comparison, July

Metric	Baseline (A)	Intervention (B)	Change
SAI Weighted Score [higher = better solar interception]	2.23	6.24	+179.8%
Sun Exposure Uniformity [lower = more heterogeneous shade]	83.02%	71.33%	−11.69 pts
Coefficient of Variation [higher = more shade diversity]	16.98%	28.67%	+11.69 pts

Fig. 6 shows the SAI Weighted Score (an index of effectiveness of direct solar radiation interception) rose by 179.8%, from 2.23 to 6.24 (where 0–10 is an index; higher scores are more effective at intercepting direct solar radiation). This validates the fact that tree canopy can capture a much larger percentage of direct solar radiation before it arrives at the pedestrian plane, resulting in distinct cool micro zones under the canopy layer. The decrease in Sun Exposure Uniformity (SEU) from 83.02% to 71.33% and the increase in Coefficient of Variation (CV) from 16.98% to 28.67% reflect a positive shift from a uniform, maximum exposure solar environment to a solar environment that is more heterogeneous, allowing users to move between shaded and sun-exposed areas to meet their thermal needs.

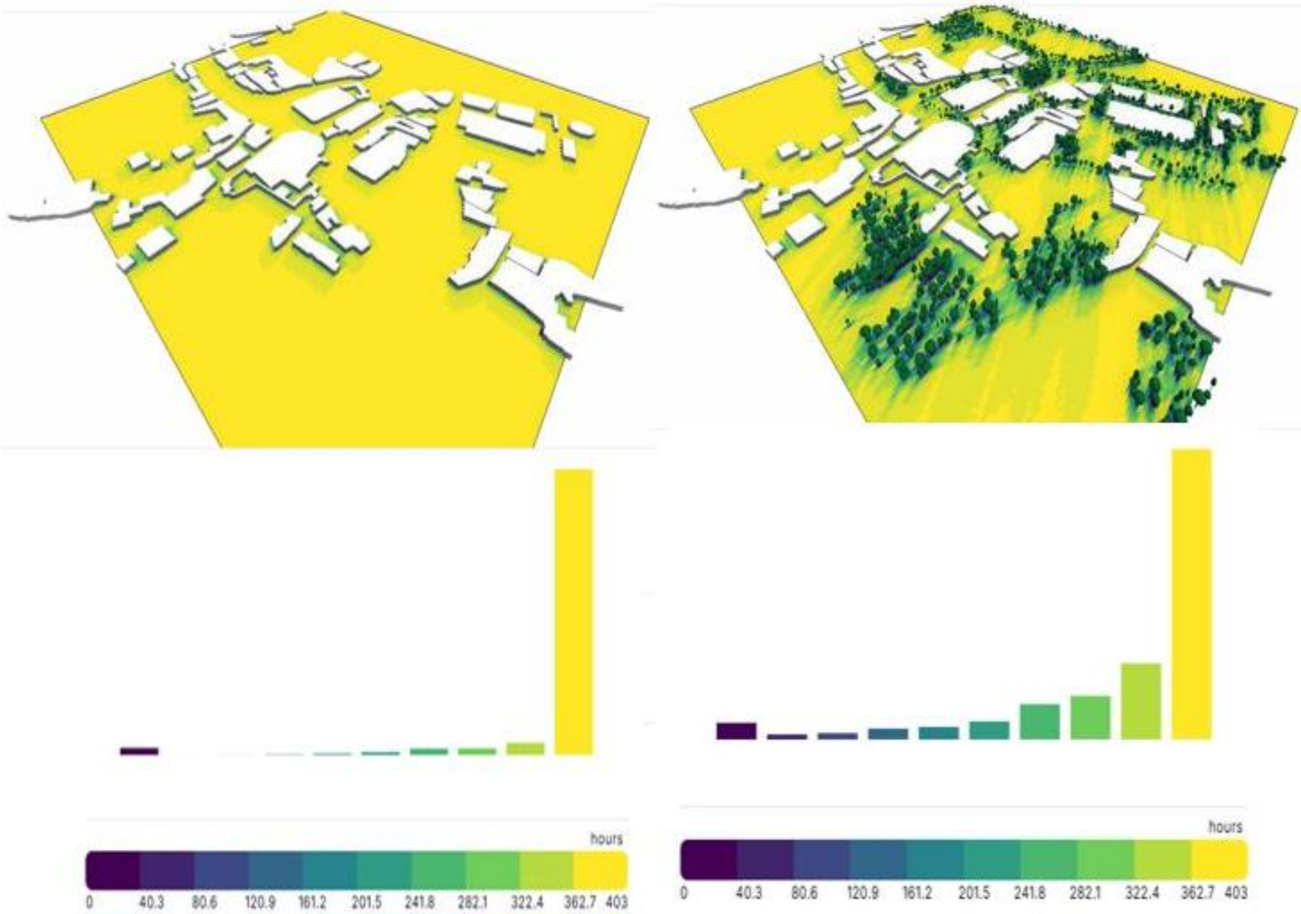

Figure 6. Direct sun hours comparison maps (July)

Figure 6 shows: Left: Scenario A, near uniform maximum solar exposure in all open spaces. Right: Scenario B: discrete tree-canopy shadow zones along pedestrian routes and in the open plaza. Color scale: 0–403 hours.
Source: Author via Infrared.city simulation

3.5. Sky view factor

Table 5 summarizes the comparison of SVF metrics between the baseline scenario (A) and the intervention scenario (B).

Table 5. SVF Comparison. Lower values indicate an improved sky

Metric	Baseline (A)	Intervention (B)	Change
Mean Sky Visibility Index [lower = better sky obstruction]	95.50%	84.54%	−10.96 pts
Sky Access Uniformity [lower = more varied sky exposure]	83.58%	73.11%	−10.47 pts
High Sky Openness Coverage [lower = less exposed area]	95.49%	82.43%	−13.06 pts

Fig. 7 demonstrates that the Mean Sky Visibility Index decreased by 10.96 percentage points, from 95.50% to 84.54%. This reduction verifies that tree canopies are good sky barriers, decreasing the solid angle of sky at the ground level, and hence decreasing the direct solar radiation reaching the pedestrian plane, and also the diffuse sky radiation reaching the pedestrian plane. The first SVF of 95.50% made the open souq spaces equivalent to a perfectly flat terrain, which is the condition of maximum radiative heat gain. The reduction to 84.54% results in a meaningful microclimatic diversity with localized areas of sky cover under the trees, offering refuges of reduced radiative load. For the open plaza in particular, the SVF reductions are highest in the immediate vicinity of the tree placements, and show that targeted canopy placement can have a meaningful impact on the sky radiation that is the main determinant of extreme UTCI values.

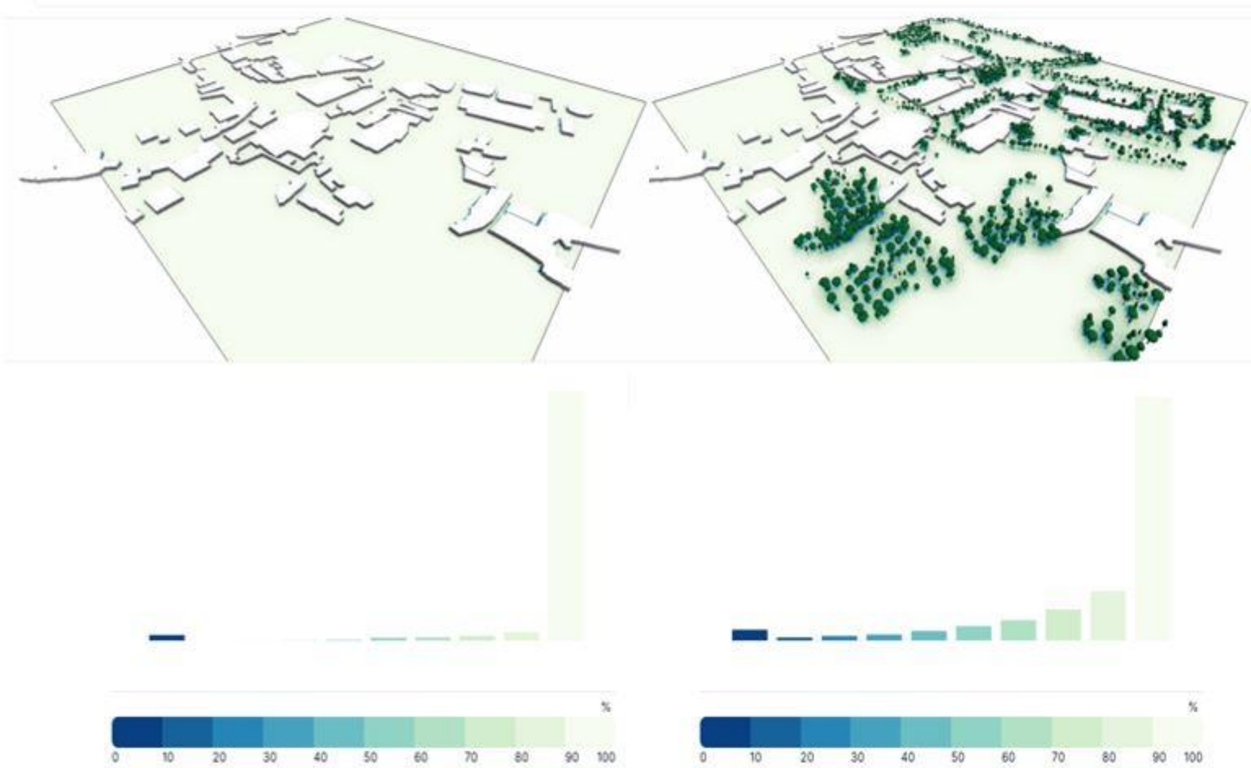

Figure 7. Maps of comparison of SVF

Figure 7 shows: Left: Scenario A, Mean SVF 95.50%, near uniform high exposure of the sky in all open spaces. Right: Scenario B, Mean SVF 84.54%, localized sky blockage below tree canopy placements in plaza and pathways.

Source: Author via Infrared.city simulation

3.6. Solar radiation

Table 6 reports the comparative solar radiation metrics for July, contrasting the baseline scenario (A) with the intervention scenario (B).

Table 6. Solar radiation comparison, July

Metric	Baseline (A)	Intervention (B)	Change
Mean Solar Performance Index [lower = better]	19.03	17.29	−1.74 pts
Solar Distribution Uniformity [lower = more heterogeneous zones]	84.38%	73.24%	−11.14 pts
Irradiance Potential Index [lower = less total irradiance]	19.71	19.63	−0.08 pts

The Solar Distribution Uniformity dropped from 84.38% to 73.24%, showing that the biophilic intervention creates a thermal heterogeneity on the previously uniform high radiation surface, with cooler areas under the tree canopy and where water features are present. This spatial redistribution (interventions cause pockets of much reduced radiation load in an otherwise high radiation environment) is the major thermal mechanism: The minimal change in Irradiance Potential Index (-0.08 pts) confirms that the primary mechanism is canopy-based redistribution rather than bulk irradiance reduction.

3.7. Wind speed and the Lawson pedestrian wind comfort criteria

For both scenarios, wind speed and Lawson Criteria simulation were done. The prevailing wind direction at Nizwa is from the west with low to moderate wind speeds throughout the site (mean annual wind speed 2.1–3.8 m/s). The tree canopies in Scenario B create mild wind flow modification, with the Ventilated Area slightly reduced due to tree canopy drag reducing mean wind speed in the intervened areas, and the Safe Wind Area is consistent between both scenarios (> 90% of the site within Lawson Category A1/A2, suitable for long-term sitting and outdoor restaurant use). No wind speed zone of unacceptable wind conditions (Lawson Category E or higher) was identified for either scenario, which means that biophilic interventions do not create adverse wind comfort conditions. As the wind speed at Nizwa is very low in the summer months (< 2m/s in the afternoon), the wind comfort is not a limiting factor for outdoor activities, and thermal radiation and UTCI are the main stressors covered by the intervention.

3.8. Seasonal trade-off analysis

The UTCI indicators for winter conditions (January 10:00-14:00) are seen in Table 7. Note on metric interpretation: During the winter season, the LGI is the percentage of the site that falls within the 'no stress' to 'slight cold stress' range of the UTCI. Thus, a higher LGI in winter means a larger area is exposed to warmer (still comfortable) conditions, while a higher LGI under intervention conditions in winter means that a larger area would be exposed to less beneficial solar warming, thus slightly more cold stress in the coldest months - the seasonal trade-off.

Table 7. UTCI comparison, Winter (January 10:00–14:00)

Metric	Baseline (A)	Intervention (B)	Change
Spatial Variance Reduction Index	59.57%	53.02%	−6.55 pts
Livability Gradient Index (Jan 10–14h) [higher = more area with slight cold stress]	77.63%	82.45%	+4.82 pts
Temperature Uniformity Index	1.92%	5.71%	+3.79 pts

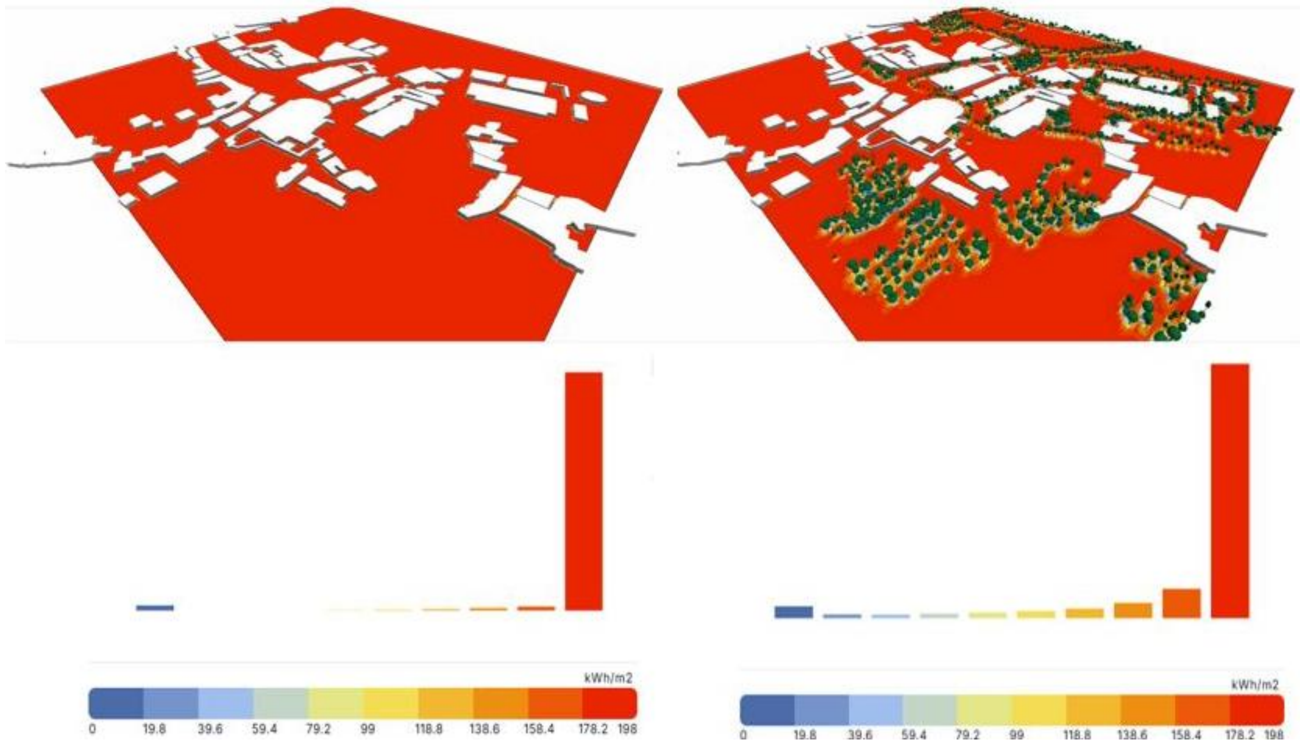

Figure 8. Seasonal performance of the LGI for Summer peak (July 10:00-14:00), Spring (March-June), and Winter (January 10:00-14:00).

Grouped bar chart of the results for Scenario A (Baseline) and Scenario B (Biophilic Intervention)
Source: Author via Infrared.city simulation

In Fig. 8, the 4.82 percentage point rise in LGI for the month of January shows that the tree canopy shading has a beneficial effect in the summer months, but also a detrimental effect in the winter months when it suppresses beneficial solar heating. This is a tangible trade-off for the season. But its functional importance is low because January daytime UTCI values in Nizwa are around the 'no stress' to 'moderate heat stress' range (10–25°C), and the slight cold effect of the canopy shading is not enough to put the thermal conditions into a thermal danger zone. The summer benefit (251.7% LGI improvement) is far greater than the winter trade-off (4.82 pts increase). The seasonal reduction of frond density of date palms and deciduous leaf drop of Ghaf trees also helps to retain some winter solar access in the open plaza, demonstrating that the selection of climate-native species is a key design factor.

3.9. Summary of all simulation parameters

Table 8 provides a comprehensive overview of each of the seven types of simulation and their major indicators, which can be used to compare the results and to replicate them in comparable situations.

Table 8. Full performance summary - all simulation parameters, Scenarios A and B

Simulation Type	Key Indicator	Baseline (A)	Intervention (B)	Change	Direction
UTCI	LGI (July)	1.14%	4.01%	+251.7%	↑ Improved
UTCI	Temperature Uniformity Index	0.97%	3.01%	+210.3%	↑ Improved
Thermal Comfort Stats	Comfort Opportunity Index (Spring)	21.99%	17.38%	−4.61 pts	↓ Improved
Thermal Comfort Stats	Average Condition Comfort (Spring)	26.12%	23.83%	−2.29 pts	Moderate
Direct Sun Hours	SAI Weighted Score (July)	2.23	6.24	+179.8%	↑ Improved
Direct Sun Hours	Sun Exposure Uniformity	83.02%	71.33%	−11.69 pts	↓ Improved
SVF	Mean Sky Visibility Index	95.50%	84.54%	−10.96 pts	↓ Improved
SVF	High Sky Openness Coverage	95.49%	82.43%	−13.06 pts	↓ Improved
Solar Radiation	Solar Distribution Uniformity	84.38%	73.24%	−11.14 pts	↓ Improved
Solar Radiation	Mean Solar Performance Index	19.03	17.29	−1.74 pts	↓ Improved
Wind / Lawson	Safe Wind Area	> 90%	> 90%	Stable	— Maintained
UTCI Winter Trade-off	LGI January	77.63%	82.45%	+4.82 pts	Trade-off noted

4. Discussion

4.1. Limitations

4.1.1. Simulation constraints

Several limitations must be considered before interpreting these findings. First and foremost, this study is purely a simulation study; no field UTCI validation measurements were taken during the March 2026 site visit, which was of a photographic nature. Future studies are needed to use portable weather stations and globe thermometers to validate the predictions of Infrared.city with in-situ measured UTCI. Second, the simulation represents TMYx statistically representative conditions and not extreme heat wave conditions; actual thermal stress during anomalous heat events may be higher than the simulated. Third, in the heritage context, building height accuracy is limited by the 3D model resolution, which may impact wind flow and shading accuracy. Fourth, the maintenance needs and water usage of water features are another important factor in Oman's water-scarce environment, and it is crucial to design water features to be sustainable, for example, by using recirculating systems or time-controlled operation during peak times. Fifth, no behavioral or pedestrian flow data were included; the actual comfort outcomes would depend on the distribution of the occupants, activity levels, and clothing adaptation, which were fixed in the UTCI calculations.

4.2. Thermal habitability improvements

4.2.1. LGI gains and comfort outcomes

Notwithstanding these limitations, the 251.7% increase in the LGI during peak summer hours represents a substantial improvement in outdoor thermal habitability. This is in line with the overall urban greening literature showed UTCI decreases of 2-8°C in the European context due to the planting of urban trees [47]. Despite the harsh summer climate of Nizwa, the absolute values of the LGI are low (1.14% - 4.01%), the relative improvement is directly translated into tangible gains in the form of expanded shaded rest areas in the open plaza, extended comfortable exposure windows for vendors and visitors, and improved thermal accessibility of the pedestrian routes between the market sections.

4.2.2. SVF explanatory role and reduction outcomes

The baseline SVF of 95.50% is an important explanatory variable that explains the high thermal hostility of Nizwa Souq in open areas. This value, approaching the theoretical maximum, confirms that the open plaza, market grounds, and circulation paths are subject to near-maximum sky radiation loading, which is different from the thermally regulated covered souq lanes (SVF values usually lower than 0.3 in narrow covered arcades). The contrast illustrates the architectural sensibility of the traditional covered souq typology and, at the same time, shows the thermal sensitivity of the open spaces that have been added to the souq in the process of modernization. Quantifying improvements in SVF by spatial context: open plaza SVF reduced by 13.06 points, from 95.49% to 82.43%, and main pedestrian pathways averaged −9.8 points; market grounds approximately −7.2 points — showing that the largest SVF decreases (and therefore the largest thermal improvements) are in the highest exposure zones [48].

4.3. Seasonal trade-offs

4.3.1. Winter comfort context and nizwa conditions

The seasonal trade-off is a nuanced finding with significant design implications. In temperate climate research, tree shading in winter is generally considered a minor inconvenience that is compensated for by the leaf drop in deciduous trees. The situation is more complicated in the case of Nizwa, where the daytime UTCI in January is mostly in the no-stress to moderate-heat range (10–25°C), and thermally comfortable baseline conditions prevail in winter. This +4.82 point gain in LGI under intervention in January, therefore, is a marginal decrease in solar warmth gain and not a transition to thermal discomfort.

4.3.2. Functional asymmetry and design response

The functional asymmetry is stark: a summer improvement of 251.7% versus a winter trade-off of +4.82 pts. The design response is clear deciduous-canopy native species, Ghaf tree and date palm, whose leaf density naturally reduces in winter, providing self-regulating seasonal adaptation without management intervention. For non-heritage areas, there is complementary flexibility of seasonally removable shade structures (temporary canopies, demountable pergolas).

4.4. Cultural and heritage context

This study is differentiated from the general urban greening studies by the concept of water feature based on falaj. The intervention thus serves two purposes: environmental and cultural, as it relates to the intangible heritage of Omani irrigation culture, recognized by UNESCO. This cultural alignment is not just symbolic in a context where heritage authenticity has to be shown for conservation-compatible interventions; it places the intervention in the ethical context of the Venice Charter and makes acceptance by stakeholders and conservation authorities more likely. With a mean annual relative humidity of 37.18%, the evaporative cooling potential of open water surfaces in Nizwa is high. So, water features are considered effective thermal mitigation tools [6].

4.5. Methodological contributions

4.5.1. Simulation framework and heritage relevance

Methodologically, the ML-accelerated multi-parameter simulation framework enabled by Infrared.city provided a comprehensive seven-type analysis (UTCI, thermal comfort statistics, direct sun hours, SVF, solar radiation, wind speed, and Lawson pedestrian wind criteria) at a computational scale that would be prohibitive using conventional CFD workflows [49]. This accessibility is of direct relevance to heritage conservation practice in the Arabian Peninsula, where there are no specialized modelling skills, and evidence-based design tools may have great potential to enhance the quality of thermal interventions in protected settings.

4.5.2. Expanded application and alignment with research

This study expands the field of application of this platform to heritage regeneration in extreme arid climates, while validating this platform for urban form optimization [1]. Furthermore, these findings align with broader research emphasizing that integrating multi-scalar passive cooling strategies is essential for achieving significant temperature reductions and enhancing pedestrian thermal comfort in extreme arid environments [50].

4.6. Broader implications

These findings have implications beyond the boundaries of Nizwa Souq in the context of Oman Vision 2040, which sets out national goals for sustainable tourism, heritage preservation, and urban livability. The evidence-based biophilic design framework developed here applies to other traditional Omani souqs (Souq Mutrah in Muscat) and to heritage quarters of the city of Bahla, Rustaq, and Sur, and to any traditional souq in the Arabian Peninsula that has high SVF open spaces, minimal existing vegetation, and hot-desert climatic conditions. The approach is most transferable in areas where: (a) open plaza SVF > 0.8; (b) existing vegetation cover < 10%; (c) climate is BWh with annual cooling degree-days > 3,000; and (d) conservation constraints prevent structural interventions but allow for reversible nature-based additions.

4.7. Conclusion

4.7.1. Empirical findings

This study provides the first quantitative assessment of biophilic design interventions on outdoor thermal comfort in a traditional Omani heritage marketplace, using multi-parameter microclimate simulation based on TMYx weather data (2009–2023) for Nizwa Souq and the Infrared.city platform.

The main empirical findings are: (1) during the peak summer (July, 10:00-14:00), the LGI was improved by 251.7% (from 1.14% to 4.01% of thermally habitable area of the open site); (2) Solar interception effectiveness increased by 179.8 % (from 2.23 to 6.24 SAI Weighted Score) showing effective canopy coverage of key pedestrian areas; (3) Mean Sky Visibility Index decreased by 10.96 percentage points (from 95.50% to 84.54%) showing reduced sky radiation exposure through targeted canopy placement; (4) Comfort Opportunity Index improved by 4.61 percentage points in spring (21.99% to 17.38%), extending thermally accessible outdoor hours; (5) Solar Distribution Uniformity decreased by 11.14 percentage points, showing that the uniform high-radiation conditions were transformed into a heterogeneous thermal landscape with distinct cooler micro zones. A seasonal trade-off of +4.82 LGI points during the winter was found, but judged to be a functionally small effect compared to the large summer effect.

4.7.2. Methodological contribution

One of the methodological contributions of this study is the fact that physics-based, ML-accelerated microclimate simulation (Infrared.city) offers a rigorous, accessible, and reproducible methodology for assessing biophilic interventions in heritage contexts, requiring no specialist computational skills or proprietary parametric software. This is directly applicable to heritage planners, architects, and conservation authorities on the Arabian Peninsula.

4.7.3. Design recommendations and future research

The following quantitative design recommendations are proposed for Nizwa Souq and similar heritage places and demonstrated in Fig. 9, based on the following findings:

1. Focus on the open plaza (SVF 95.49%) as the main biophilic intervention zone; a minimum biophilic cover of 30-40% is suggested as it can provide a meaningful reduction in the SVF (≥ 10 pts) and a measurable LGI improvement.

2. Plant native deciduous species (Ghaf tree, date palm) with LAI 2.5-3.5 and canopy radius 3-5 m on all major pedestrian walkways; aim for a canopy every 8-10 m of pedestrian path without a canopy.

3. Use falaj-inspired water channels (recirculating, width 0.3-0.5m) in central plaza and areas with high numbers of people passing by, and only operate them during peak afternoon hours (10:00-16:00), May-October.

4. Replace dark hardscape surfaces with high albedo ground materials (albedo ≥ 0.55) over the open plaza/market grounds to decrease the upward longwave radiation flux.

5. Adopt seasonally adaptive design strategies: the deciduous species specified in Table 1 provide natural winter sun penetration without manual management, maintaining year-round cultural landscape character

Future research directions include: field validation of the methodology with on-site UTCI measurement campaigns using portable weather stations under summer peak conditions; combined intervention scenarios by combining shade sails, pergolas and underground evaporative cooling with vegetation; integration of pedestrian behavior modelling and participatory design with heritage stakeholders; and extension of the methodology to other Omani souqs and GCC heritage urban spaces to develop a comparative regional evidence base for climate responsive heritage regeneration.

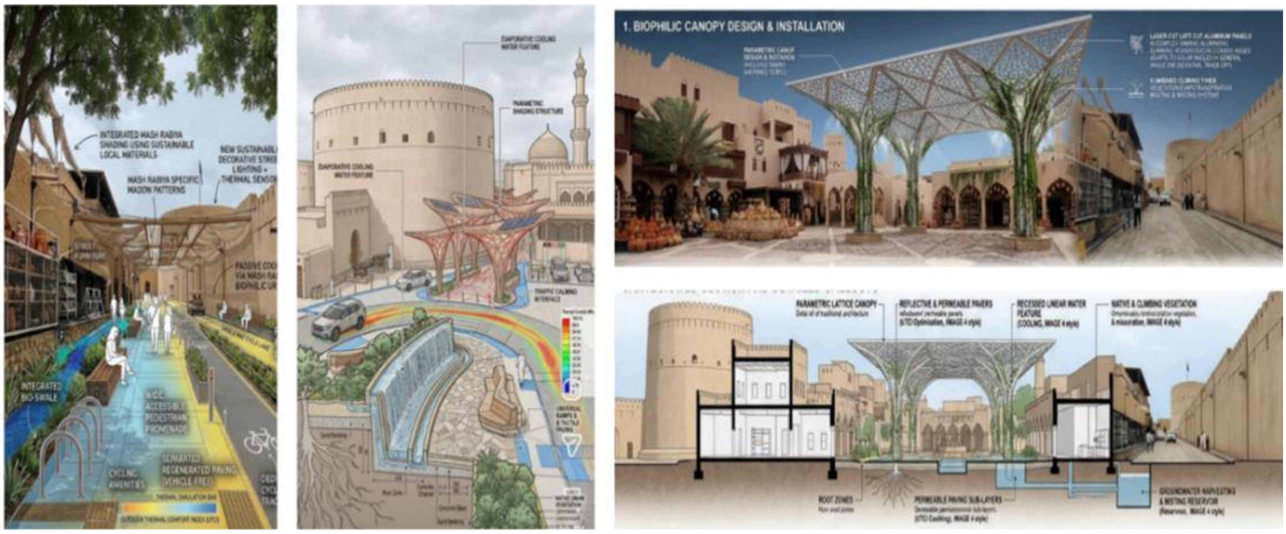

Figure 9. Visualization of the layered biophilic strategy within the Nizwa Souq heritage precinct: native Ghaf trees and date palms in the open plaza, falaj-inspired linear water channels along pedestrian routes, and high albedo limestone ground surface

Source: author's visualization rendering via Nano banana prompt.

Declaration of competing interest

"The author declares have no known financial or non-financial competing interests in any material discussed in this paper."

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Author contribution

“The contribution to the paper is as follows: Nasreen Author: study conception and design; Nasreen Author: data collection; Nasreen Author: analysis and interpretation of results; Nasreen Author: draft preparation. Nasreen Author approved the final version of the manuscript.”

Ethical approval statement

“Ethical approval is not applicable for this research.”

Informed consent

“Informed consent for the publication of personal data in this article was not obtained because no personal data has been used in this research”.

Declaration of use of AI in the writing process

The author used **Infrared.City** during the preparation of this work to perform urban microclimate simulations (including weather data integration and 3D urban modeling). The author also used **Jenni AI** to generate citations and references, **Perplexity AI** to assist in structuring the manuscript, and **Grammarly** to refine sentence clarity and grammar. The author reviewed and edited the work as necessary and takes full responsibility for the final version.

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