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Climate adaptation in informal areas in hot arid climates

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Abstract

This conceptual and exploratory research study investigates, systematically and holistically, climate-adaptive spatial design interventions for high-density informal urban areas in hot arid climates, which remain understudied despite their vulnerability to heat stress and the heat-vulnerable groups populating them. Five streetscape design prototypes are proposed that include climate-adaptive spatial interventions appraised qualitatively with consideration to relevant feasibility matters: land use planning, equity, affordability, mobility, and sense of place. The study shows that there is potential for climate-adaptive interventions in informal urban areas in hot arid climates, but that these interventions also present challenges. Common climate-adaptive design strategies can be used to address heat stress in these areas but, for example, increasing vegetation might be challenging due to water stress. As a conceptual study, the findings presented and the discussion raised on feasibility are targeted at opening avenues for future research, and at informing decision-makers and spatial designers.

KEYWORDS

climate adaptation, climate-adaptive design, heat stress, heat-vulnerable groups, hot arid climates, informal urban areas

1 | INTRODUCTION

Over one billion urban dwellers in the global South are estimated to live in informal settlements (Satterthwaite et al., 2020). These settlements result from rapid population growth and a scarcity of higher-quality, lower-cost alternatives. They can occur in planned and unplanned urban areas, both state-owned and private land, such as riverbanks, and agricultural or vacant lands inside or outside cities (Karunarathne & Lee, 2022). While definitions of urban informality seem to remain elusive and contested, these areas are generally associated with insufficient urban infrastructure, such as clean water, sanitation, or public transportation, insufficient urban services, such as access to healthcare or education (Bek et al., 2018), limited security of tenure, poor housing quality, and unsafety.

In light of the climate crisis, one of the aspects that ought to be considered during the upgrading of existing informal urban areas is their capacity to cope with heat stress, especially in the harsh hot arid climates. Current climate change models predict that the air temperature globally will rise between 3°C and 4°C within this century (New et al., 2011). Raising temperature increases mortality and morbidity rates, especially amongst the most vulnerable groups (Coates et al., 2022; Marincic & Ochoa, 2021; Wang et al., 2021), such as children, the elderly, and cardio-vascular or depression patients (Cheng et al., 2021; Gasparrini et al., 2015).

In addition, the impacts of climate change, particularly heat waves in urban areas, are likely to more strongly affect developing economies which, simultaneously, may have limited adaptive capacity (Srinivasan, 2010). People living in informal urban areas are particularly vulnerable to heat stress because they tend to live in crowded multiunit housing with poor ventilation and insulation. The compact composite of buildings and insufficient access to open spaces in these settlements represent further risks to inhabitants. Densely built-up land alters wind patterns, surface radiation balance, and air temperature conditions near the ground. High height-to-width ratios (*H*/*W*) and low sky-view factors (SVF) may impede outdoor and indoor ventilation, as well as night-time longwave radiation (Ali-Toudert et al., 2005). The trapped longwave radiation within urban canyons combined with little or no ventilation significantly influences urban microclimates and, in particular, heat stress (Morakinyo et al., 2017), and heat storage within buildings. In informal urban areas, this storage is further accentuated by the predominant use of low albedo building materials (Galal et al., 2020; Jaber, 2022).

Climate-adaptive spatial design aims to increase the capacity of urban populations "to cope with the impacts of climate change in ways that maintain a shared urban identity" (Cortesão & Copeland, 2021). The body of knowledge in this field is substantial and offers vital information for sustainable urban development and urban resilience. However, the study of climate-adaptive design for high-density informal urban areas in hot arid climates remains limited and poses unique challenges due to the combination of a harsh climate type and the limited availability of regulatory instruments and financial means to adapt to climate change.

Fueled by these concerns, this study addresses the question: what climate-adaptive spatial design interventions are most feasible in high-density informal urban areas in hot arid climates? This qualitative, interdisciplinary research study investigates systematically and holistically, with research through design (RTD), feasible climate-adaptive spatial design interventions in high-density informal urban areas in hot arid climates. The aim of the paper is to propose a conceptual framework for the identification and implementation of climate-adaptive streetscapes in these areas. An informal neighborhood in the Shubra district, Cairo, is used as a study case to develop prototypical climate-adaptive spatial interventions potentially replicable across informal urban areas in Cairo, and other cities in hot arid climates.

While previous studies on climate-adaptive design in hot arid climates have primarily been focused on the application of vegetation and/or cooling materials (Faragallah & Ragheb, 2022; Loh & Bhiwapurkar, 2022) mostly detached from social, cultural, and technical aspects (such finance or mobility), this study offers a wider, interdisciplinary, and therefore more holistic, approach to addressing these matters. Our aim is to enrich climate-adaptive studies in hot arid climates with a wider spectrum of possible spatial interventions, and by incorporating a broader range of topics relevant to the feasibility of these interventions. With an interdisciplinary lens, we selected land use planning, equity, affordability, mobility, and sense of place as key feasibility considerations. Our focus on informal urban settlements in hot arid climates also makes an important contribution to the field of climate-adaptive design, which has generally overlooked these contexts. Our use of an expanded RTD approach also offers a methodological contribution, demonstrating how insights from several disciplines can be feasibly incorporated into the design of high-density informal urban areas in hot arid climates. With these contributions, we hope to open up avenues for future research, and inform decision-making and spatial design practice in these locations.

The following section presents the qualitative interdisciplinary methodology used to develop the design prototypes (Section 2). The results section presents the five prototypes created (Section 3). The discussion reflects on the feasibility challenges (and opportunities) that the interventions comprised in the prototypes might be faced with (Section 4). The conclusion summarizes our main findings, and provides recommendations for future research (Section 5).

2 | MATERIALS AND METHODS

2.1 | Study area

An informal neighborhood in the Shubra district (Figure 1) was selected in collaboration with researchers of the *Smart & Future Cities Laboratory for Sustainable Urban Solutions*, Ain Shams University, as a location for conducting this study due to its spatial, (micro)climatic, and social characteristics. With a total population of approximately 81.000 inhabitants (CAPMAS, 2018) and an area of about 20 ha, Shubra comprises formal and informal areas. The area selected for this study (Figure 1) is roughly 1.4 km^2 in area and is bordered on the East by the Emtedad Ahmed Helmi road and the national railway line, on the West by El Teraa Al Bolakia street, on the South by the Ahmed Badawi street, and on the North by the Moerkous Somoail street.

The intricate urban geometry, prevalent high *H*/*W*, lack of vegetation and porous materials and/or moisture-trapping surfaces, and predominance of sealed surfaces (asphalt) all contribute to the climatic vulnerability of this neighborhood located at the heart of Cairo's surface urban heat island (Figure 1). The most common building materials at Shubra are concrete and bricks, which absorb and retain high amounts of solar radiation (Wonorahardjo et al., 2020). There is also a noticeable lack of plastering or painting, resulting in the low thermal resistance of the outer walls of buildings (Mohammad & Shea, 2013). Additionally, buildings possess low albedo flat roofs and poor thermal insulation, especially when built of improvised materials such as tin or plastic sheets.

According to the Köppen climate classification of Greater Cairo (Kottek et al., 2006), these characteristics are exacerbated by the hot arid climate type. The predominant wind direction in Cairo is northerly, and wind speeds are sufficient to penetrate the Urban Canopy Layer (Robaa, 2003). The winter months are December to February, when it is relatively humid and there is little rain. Summer is hot, dry, and rainless from July to August. The annual rainfall amounts to approximately 20 mm, and the rainiest months are January–June, and October–December (Climate and Average Weather Year-Round in Cairo, 2022). The average daily mean temperature in January amounts to 19.7°C and

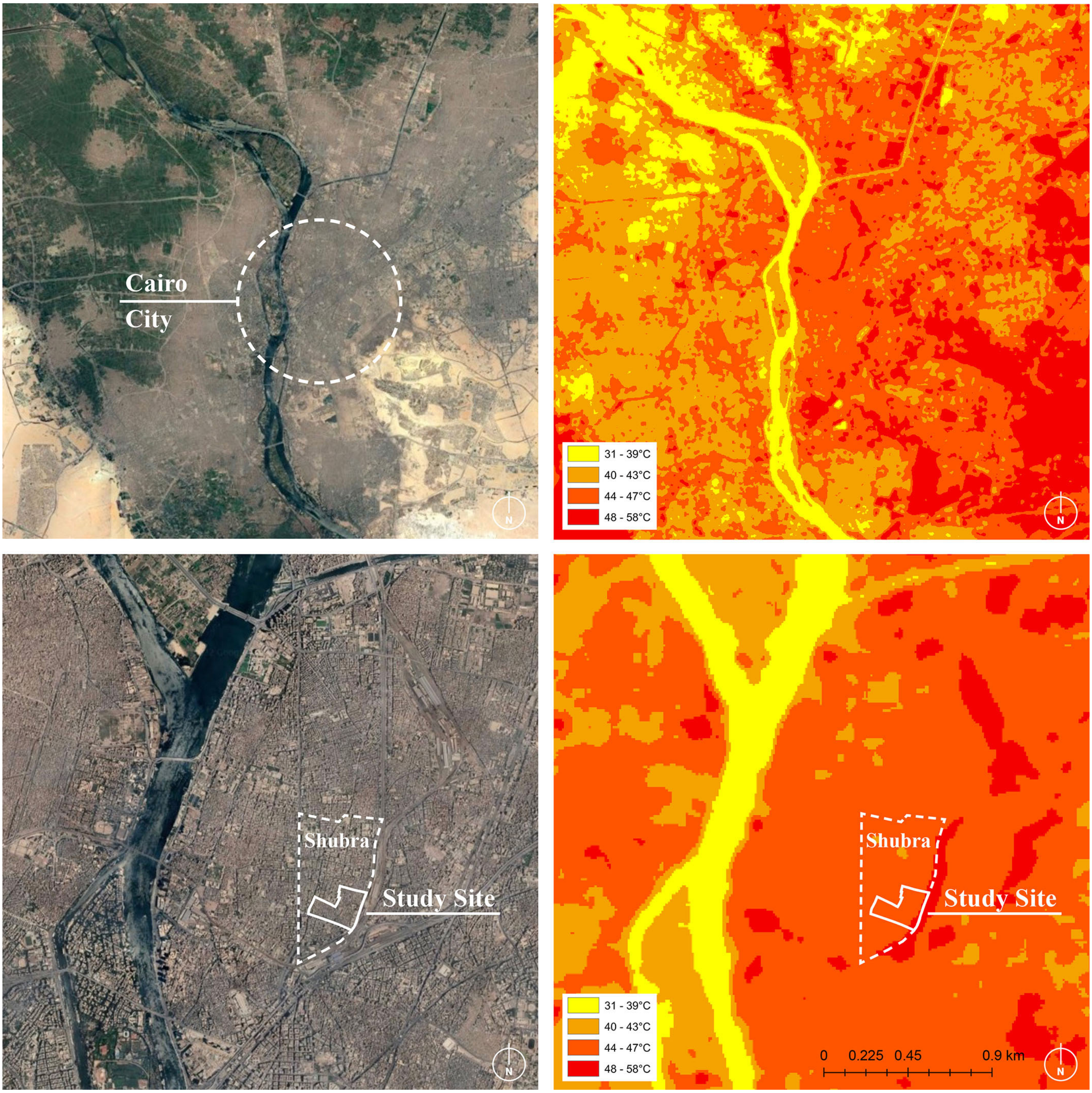

FIGURE 1 The Shubra district: its location within Cairo (left-hand side) and within the daytime surface urban heat island (right-hand side). LST was mapped using Google Earth Engine Open-Source Code (https://developers.google.com/earth-engine/datasets/tags/lst) for LST estimation from the Landsat series, and calculated for July 1–15, 2022.

34.9°C in July (Robaa, 2013). The average annual temperature amounts to 22°C (El Kenawy et al., 2020). Cairo is relatively flat and surrounded by desert from the South, west, and east, making the city vulnerable to shortwave radiation, and high air and surface temperatures. In addition, the high population and building density of Cairo, combined with the insufficient public transportation system, leads to high car dependency, a major source of anthropogenic heat in Cairo.

None of the physical and climatic challenges described above are unique to Shubra but recurrent in high-density informal urban areas in Greater Cairo, which represent almost 70% of its area (Elmouelhi, 2022). Shubra is, thus, a case suitable for developing climate-adaptive design prototypes replicable across informal developments in Cairo.

2.2 | Methodology

This study employed qualitative interdisciplinary methods during an RTD process (Figure 2). RTD is a scientific approach to design studies

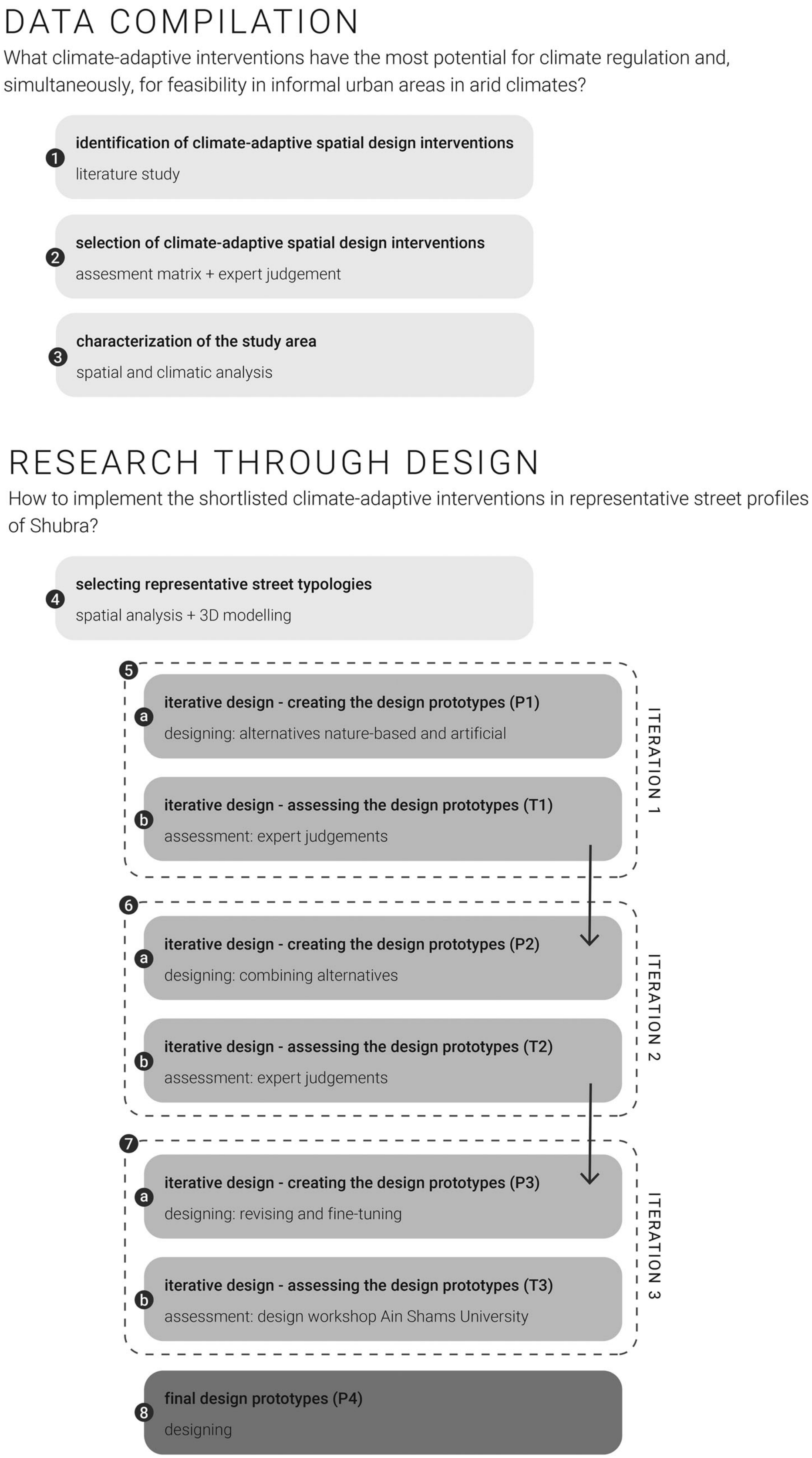

FIGURE 2 Flowchart of the eight iterative steps within the Research Through Design employed in this study. P1–P4 denote the different versions of the prototypes; T1–T3 denote the testing stages.

that iteratively develops and tests/assesses various design propositions until the highest-ranked proposition(s) is identified (Cortesão & Lenzholzer, 2022).

This RTD comprised three iterations preceded by a data compilation stage, targeted at creating the design prototypes. Designing involved sketching, 2D drawings, and 3D modeling in SketchUp

(3D modeling software), where the sun/shade model was built for solar noon (1:00 p.m. GMT + 2) on the local longest day of the year (21 June). The design interventions were developed over representative street profiles of Shubra, so that the prototypes could be replicable. The designing stages are referred to as “P” (for prototype) followed by the digit identifying each typology (thus P1–P4). Testing involved the judgments of seven experts in the fields of climate-adaptive design, urban climate, land use planning, equity, urban finance, mobility, and architecture. These experts were affiliated to Wageningen, Chicago State, Delft, and Ain Shams Universities, and were selected based on their track record on these fields. Each expert assessed the designs on one out of seven criteria: “leading to cooling effects” (climate-adaptive design); “reduction of the urban heat island” (urban climate); “fostering integrated land use planning approaches” (land use planning); “fostering equity” (equity); “dealing with affordable interventions” (urban finance); “inclusion of local movement needs” (mobility); and “contribution to sense of place,” that is, a design fitting local spatial and social idiosyncrasies (architecture). Each criterion was rated on a five-point Likert scale, where 1 indicated “low feasibility,” 2 “some feasibility,” 3 “feasibility,” 4 “high feasibility,” and 5 “very high feasibility”. An interdisciplinary discussion on the reasons behind the ratings followed, in order to pinpoint which aspects needed improvement in the following iteration. The testing stages are referred to as “T” (for test) followed by the digit identifying each typology (thus T1–T3).

2.2.1 | Data compilation

We first collected and processed all data necessary for undertaking the RTD iterations guided by the question: what climate-adaptive interventions have the most potential for climate regulation and, simultaneously, for feasibility in informal urban areas in hot arid climates? This stage followed the steps and activities below (see also Figure 2).

Step 1. Identification of climate-adaptive spatial design interventions.

This was a review of scientific peer-reviewed original research papers written in English to identify climate-adaptive interventions suitable to hot arid climates. The following search terms were plotted in Google Scholar: (urban climate OR climate-adaptive design OR climate-responsive design OR climate-conscious design OR bioclimatic design); AND (hot arid climate); OR (temperate climate). Because information on climate-adaptive spatial design is scarce for hot arid climates, the literature review included temperate climates to identify interventions eventually applicable to hot arid climates too. The interventions were also selected under the advice of the Ain Shams University experts, to ensure their appropriateness to local communities.

Step 2. Selection of climate-adaptive spatial design interventions.

The interventions found in step 1 were categorized into three groups of climate-adaptive design strategies (Table 1): adapting urban materials (increasing albedo values and/or changing specific heat properties of surfacing materials), implementing shade (blocking direct solar radiation by implementing artificial shading structures), and introducing vegetation (provision of cooling through shading and evapotranspiration). These are cooling strategies widely validated by previous studies (e.g., Klemm, 2018; Lenzholzer, 2015; Tsoka, 2017; Cortesão et al., 2020). The interventions were assessed regarding their capacity to reduce short- and longwave radiation and air temperature, regulate ventilation, and increase evaporative cooling.

Step 3. Characterization of the study area.

This step collected data on the study area's spatial, social, and climatic characteristics. We began with a spatial analysis utilizing cartographic material, aerial photos, and a literature study. Subsequently, we varied out a climatic analysis using data from official climate data websites and in the literature. Finally, we conducted three visits to the study area.

2.2.2 | Research through design

The RTD stage dealt with applying the design interventions identified in the data compilation stage over representative street profiles of Shubra (step 4) in combinations and configurations fitting the layout and functions of each profile and its cooling needs. This took place from iterations 1–3 (steps 5–7) and was guided by the question: how can the shortlisted climate-adaptive interventions be implemented in representative street profiles of Shubra? This stage comprehended the steps and activities below (see also Figure 2).

Step 4. Selecting representative street typologies.

Creating the design interventions in representative street profiles of Shubra enabled working with urban environments not specific to a site, which serves the replicability of design prototypes (Cortesão et al., 2020). Four street typologies were identified with the data gathered in step 3 based on: *H/W*, street orientation, type and condition of adjacent buildings, mobility, predominant functions at the street level and buildings, and recurrence within Shubra (Figure 3).

The final typologies (Figure 4) are now described in an illustrative manner:

- *Typology 1 | narrow street north–south and east–west (N/S–E/W)*: Street with an average width of 5 m, confined by a plethora of building heights, mostly between 6, 9, and 12 m, which results in high *H/W* ratios (2:1 and 1:1). Despite the limited space this profile might comprise trees. The ground surface is often unpaved, sometimes asphalted, and typically there are no sidewalks. These are local streets where the predominant functions are residential, small-scale, informal commercial activities (e.g., street vendors), motorized and pedestrian traffic, car parking, and social meeting.

TABLE 1 Design interventions identified with the literature review shortlisted after the expert's assessment.

Strategies	Climate-responsive design interventions		
Adapting urban materials	• High albedo surfaces • Cool surface material • Depaving		
Implementing shade	• Vertical and horizontal shading elements (facade): ○ Window shutters ○ Canvas screening ○ Green screening ○ Awnings	• Canopies: ○ Canvases ○ Pergolas ○ Louvres ○ Colonnades	• Vertical shading structures
Introducing vegetation	• Trees • Shrubs • Ground cover vegetation • Planters • Vegetated facade		

FIGURE 3 Spatial overview of the representative street typologies T1–T4 identified, and their distribution within the Shubra district. "T" stands for typology.

- *Typology 2* | *medium street N/S* (this typology was not found for the E/W orientation): Street with an average width of 20 m and predominant building heights between 9, 12, 15, and 18 m, resulting in medium to high H/W ratios (1:2 and 1:1). Trees, shrubs, and creepers may be found along the building facades. Sidewalks are minimal, and the streetscape is dominated by motorized traffic. These are secondary, fully asphalted roads connecting neighborhoods. The predominant functions are residential, small local businesses and informal commercial activities, motorized and pedestrian traffic, and car parking.
- *Typology 3* | *wide street N/S-E/W*: Street with an average width of 38 m and predominant building heights between 12, 15, and 18 m, resulting in low H/W ratios (1:3 and 1:2). Trees can be found on

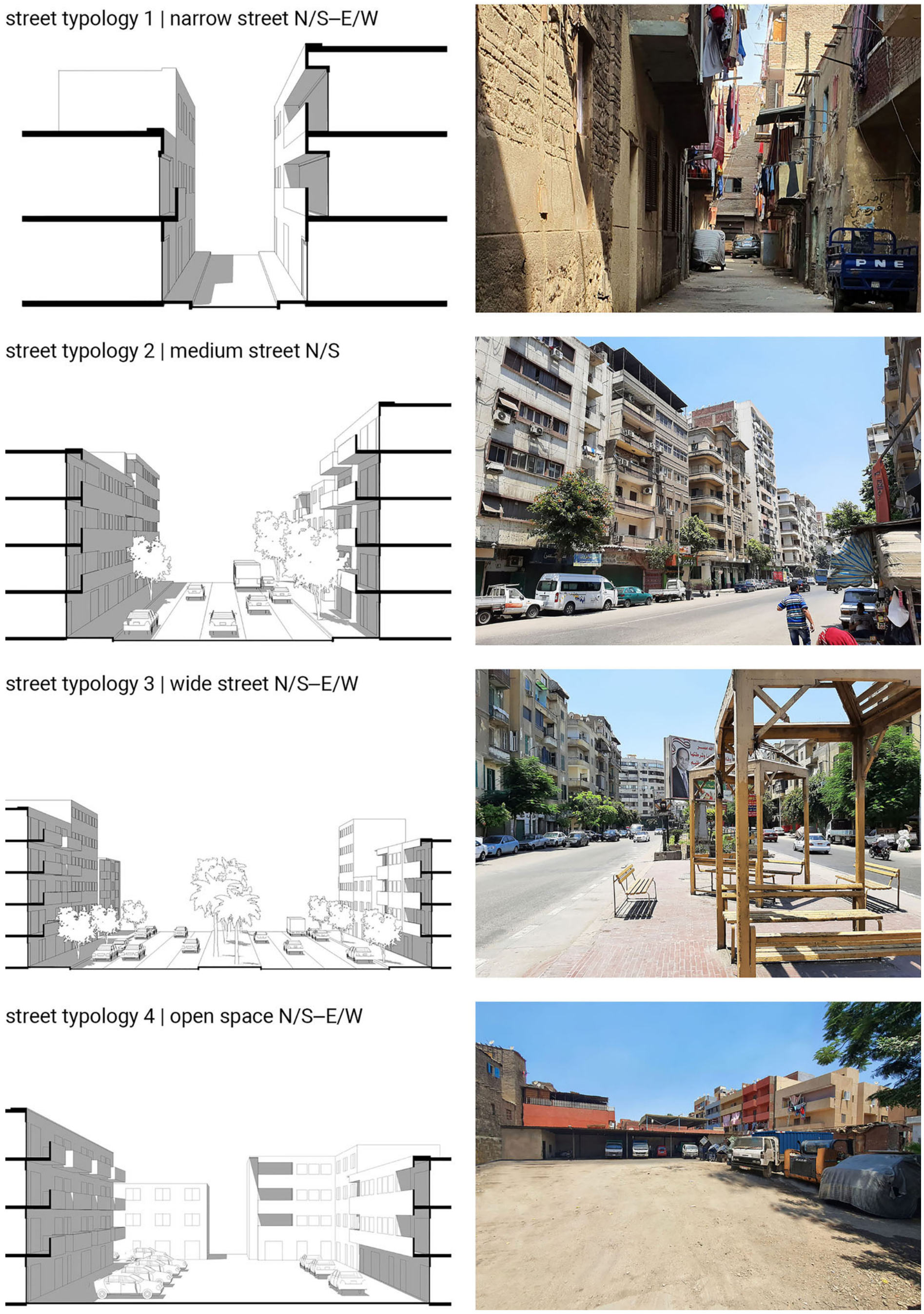

FIGURE 4 Overview of the four representative street typologies identified in Shubra: 3D schematic view (left-hand side), and reference picture (right-hand side).

sidewalks, which are predominately wider than in other street profiles. Car lanes are split by a central traffic island, varying in size and materials. These are primary, fully asphalted roads connecting neighborhoods. The predominant functions are residential, local businesses, motorized (mostly heavy) and pedestrian traffic, and car parking.

- *Typology 4* | *(semi-) open space N/S–E/W*: Semi-open and open outdoor spaces were found to vary tremendously in shape and size. For simplicity, we considered an averaged 625 m^2 squared space. These spaces may function as parking spots, markets, or schoolyards and, thus, might be closed off. Trees are almost never present. These spaces are mostly surrounded by residential buildings of varying heights and can be accessed via narrow streets (Typology 1).

Steps 5a and 5b. Iteration 1: creating (P1) and assessing (T1) the prototypes.

The first design iteration (P1) comprised two design alternatives for each typology: nature-based (implementing vegetation only) and artificial (implementing human-made elements only, such as canvas canopies). The former referred to a situation where planting would be possible, whilst the latter to another where planting would be impossible (e.g., due to high H/W ratios or underground cabling). The P1 alternatives were assessed and discussed on the aforementioned seven criteria and rating scale (T1).

Steps 6a and 6b. Iteration 2: creating (P2) and assessing (T2) the prototypes.

In iteration 2, the nature-based and artificial interventions scoring the highest (rate 3 – "feasibility" or higher) in T1 were merged into one design per street typology (P2). The negative scoring interventions were refined or dropped out. The testing of P2 (T2) followed the same procedure as T1 to assess if the combinations of nature-based and artificial interventions successfully withhold or even improve the potentials on the suitable criteria identified in T1.

Steps 7a and 7b. Iteration 3: creating (P3) and assessing (T3) the prototypes.

T2 confirmed the potential of P2 but also led to the revision of interventions scoring low on finance (mostly high maintenance requirements) and mobility (mostly the impairment of car circulation). The designs were revised by introducing shared space and replacing costly interventions with lower-cost ones (P3). As iteration 3 was primarily concerned with fine-tuning the prototypes in terms of feasibility in the study area, T3 included insights from landscape architecture, urbanism, urban design, and architecture students from Egypt, during a one-day design workshop at the Ain Shams University. This workshop was organized and supervised by member of the research team and teaching staff of the Ain Shams University experienced with local communities. The 30 participants in this workshop were challenged to develop climate-adaptive design interventions over the street typologies defined in this study. By this means, participants would (indirectly) assess the feasibility of P3 and, thereby, enable the validation, elimination, and/or expansion of its interventions. To prevent bias, P3 was not presented, mentioned, or suggested in any way.

The Ain Shams University workshop served to provide a crucial moment of local feedback, in a process with a number of limitations (time available for conducting the research, budget, language barrier, and sensitive socio-political constraints at the study area).

Step 8. Defining the final prototypes (P4).

We distilled and categorized the design interventions developed in the workshop as interventions that validated, contradicted, and added to those in P3 (Table 2). As shown in Table 2, most interventions proposed during the workshop matched those included in P3 although some groups proposed alternative ways to produce them (e.g., palm tree leaves for shading canopies instead of canvas). One intervention diverged from P3, but was still kept due to its cooling potential: while in P3 large vegetation and vertical screening structures provide shade on balconies, some participants suggested low vegetation (e.g., edible herbs). Two interventions were added to P3 due to their climate-adaptive potential and feasibility in the local context: rotating louvers (shading devices made of blades that can be pivoted according to the sun angle) and *qullah* (a traditional Egyptian and Persian passive cooling system that directs airflow to underground water reservoirs where the air is cooled down through evaporation and subsequently directed indoors). Interventions that were cost-intensive, hard to implement, or compromise the structural stability of the buildings (e.g., green roofs) were discarded. This process refined P3 and originated the final design prototypes (P4).

3 | RESULTS

The process described in the previous section resulted in five design prototypes for climate-adaptive streetscapes in informal urban areas in hot arid climates (P4) that include climate-adaptiveness, land use planning, equity, affordability, mobility, and sense of place criteria. The spatial interventions these prototypes comprise are replicable, suggestive and should, thus, be tailored to local circumstances. This section presents these prototypes and the results of their testing.

3.1 | Prototype 1 | narrow street N/S–E/W

Prototype 1 (Figure 5) combines small-scale climate-adaptive design interventions from the three groups of climate-adaptive strategies comprised in this study:

- Adapting urban materials: The albedo of facades and ground surfaces is increased by applying light-colored paint or by re-coating them with cool surface materials. Depaving and/or use of loose permeable ground covers (e.g., gravel or bare soil) should take place as much as possible but in ways that allow car circulation and minimize dust formation, especially during sandstorms (depending on street orientation).
- Implementing shade: The street is shaded by canvas canopies that are retractable to allow ventilation and longwave radiation. Natural ventilation is further enabled by placing these canopies at different heights, which allows adjusting them to varying wind speeds and directions between summer and winter. Building facades are shaded by vertical and horizontal shading elements, amongst which the *qullah*.
- Introducing vegetation: Trees, shrubs, and ground covers are not suitable for this narrow street profile as they may trap longwave radiation and block wind, and impair the transit of people and vehicles. However, climbing vegetation can cover facades, directly planted on the ground or raised planters.

The results of the expert judgments (Table 3) show that the feasibility of this prototype was improved for all criteria between the two testing rounds. Eventually, the combined version (P2) received approximately the same scores in iteration 2: 4 (high feasibility) and 5 (very high feasibility). The lowest score was for equity: 3 (feasibility). The match of design interventions included in P3 with the ones proposed in the Ain Shams University workshop (Table 2) indicates the adequacy of the interventions comprised in prototype 1.

TABLE 2 Overview of design interventions proposed during the design workshop at the Ain Shams University, and how they relate to the interventions comprised in P3.

Confirm	Question	Add	Discarded
• High albedo surface • Cool surface material • Depaving • Vertical and horizontal shading elements (facade) • Canopies (canvas, pergola, louvre, colonnades) • Vertical shading structure • Trees • Shrubs • Ground cover vegetation • Planters • Vegetated facade	• Green screening	• Rotating louvres • Passive cooling system *qullah*	• Wind catcher • Solar chimney • Green roofs • Turf stone pavement • Water elements

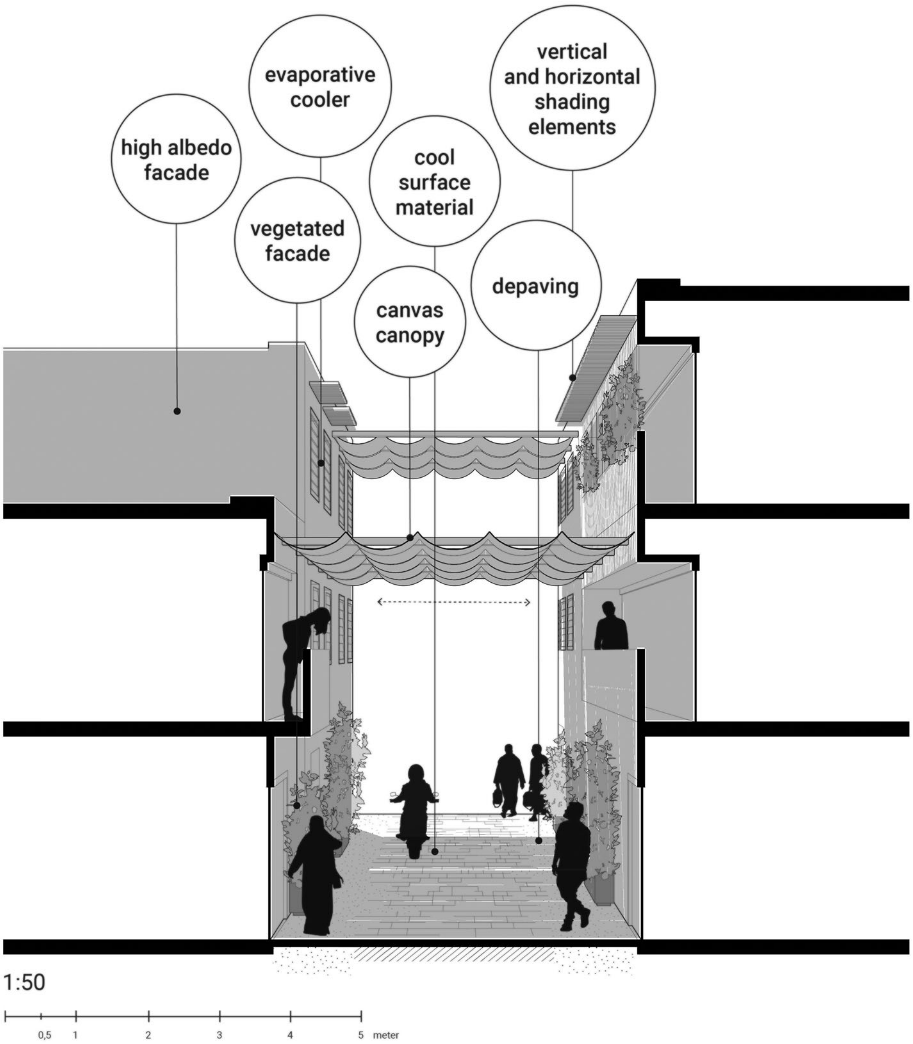

FIGURE 5 Illustration of design prototype 1 | narrow street.

3.2 | Prototype 2 | medium street N/S

Prototype 2 (Figure 6) combines small- and large-scale climate-adaptive spatial design interventions from the three groups of climate-adaptive strategies comprised in this study:

- Adapting urban materials: The albedo of facades, ground surfaces, and roads can be increased by applying light-colored paint or re-coating them with cool surface materials. Depaving should occur as much as possible but in ways that allow car circulation. For example, depaved strips can be applied along the sidewalks

TABLE 3 Testing results for prototype 1 | narrow street N/S-E/W based on the score ranges from 1 to 5.

		Climate-adaptive design	Urban climate	Land use	Equity	Affordability	Mobility	Sense of place
Iteration 1	P1 nature-based	4	3	3	3	3	4	3
	P1 artificial	4	4	3	4	3	2	4
Iteration 2	P2 combined	5	4	5	3	4	4	5

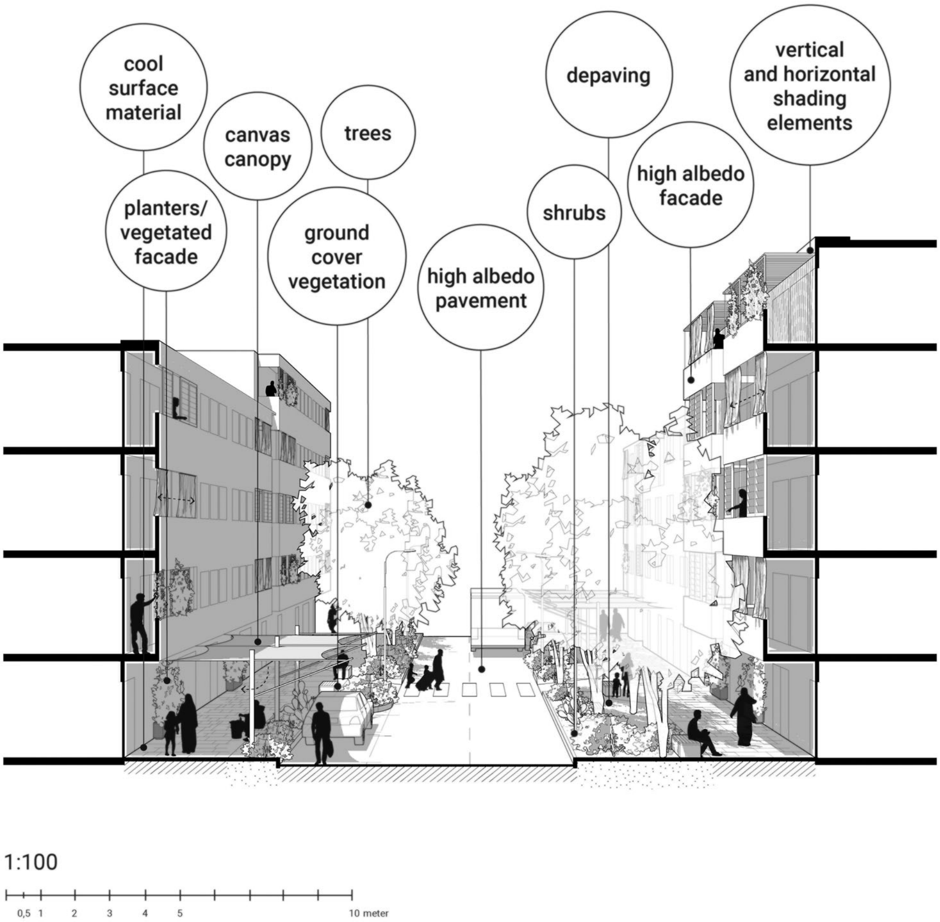

FIGURE 6 Illustration of design prototype 2 | medium street.

to provide protection from car traffic and create space for vegetation.

- Implementing shade: Building facades can be protected from incoming solar radiation with vertical and horizontal flexible shading elements (e.g., rotating louvres, sliding canvas screenings, or curtains). These vertical elements block the low midday sun on east and west facades, and the horizontal elements protect North- and south-facing facades from the high midday sun. Green screening (i.e., vegetated panels on balconies) provides additional cooling by evapotranspiration. Sidewalks and parking spots can be shaded with flexible canopies (e.g., canvas canopies) to allow daytime shading, night-time longwave radiation, and ventilation.
- Introducing vegetation: Trees, shrubs, and ground covers can be planted in the depaved strips along the sidewalks. Trees and higher shrubs should be planted interspersed to prevent the trapping of longwave radiation, of exhaustion fumes, and the blocking of wind (more effective when the prevailing wind direction is parallel to the street). Ground covers can be combined with trees and shrubs to reduce their vulnerability to damage by stepping or abusive car parking. These green pockets are alternated with parking spots not to compromise mobility and functionality (e.g., deliveries to shops). Climbing plants can cover in facades, directly planted on the ground or raised planters.

The results of the expert judgments (Table 4) show that in most cases, this prototype scored either higher or the same as in the testing of iteration 1. This indicates that the final prototype is feasible, with scores of 4 (high feasibility) and 5 (very high feasibility) for most criteria. The lowest score was on affordability: 3 (feasibility). The match of design interventions included in P3 with the ones proposed in the Ain Shams University workshop (Table 2) indicates the adequacy of the interventions comprised in prototype 2.

TABLE 4 Testing results for prototype 2 | medium street N/S based on scores ranges from 1 to 5.

		Climate-adaptive design	Urban climate	Land use	Equity	Affordability	Mobility	Sense of place
Iteration 1	P1 nature-based	4	4	3	4	3	3	3
	P1 artificial	4	5	5	3	5	3	4
Iteration 2	P2 combined	5	4	5	4	3	4	4

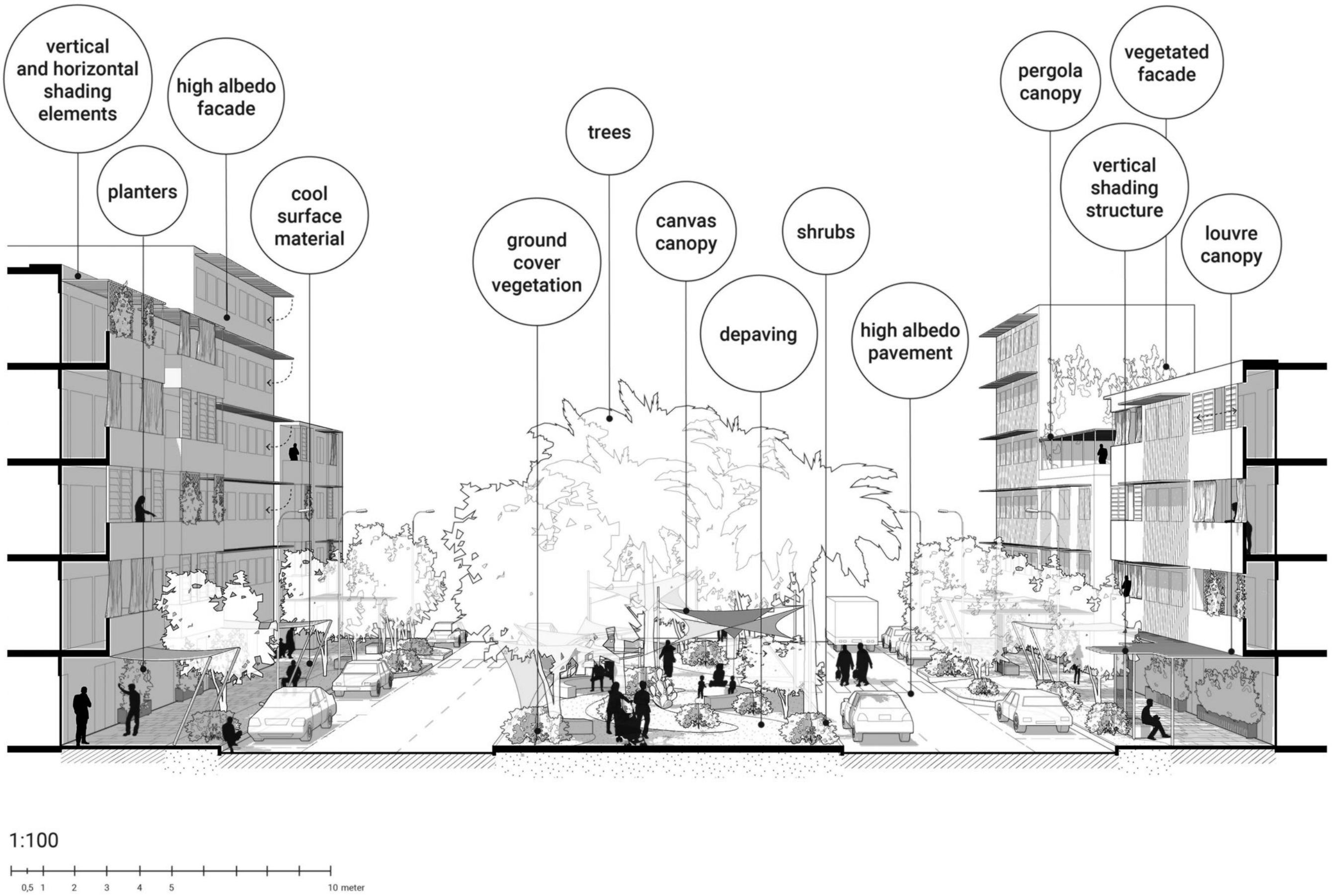

FIGURE 7 Illustration of design prototype 3 | wide street.

3.3 | Prototype 3 | wide street N/S–E/W

Prototype 3 (Figure 7) includes the same interventions as prototype 2, although this wider street allows including more and larger interventions from the three groups of climate-adaptive strategies comprised in this study:

- Adapting urban materials: The middle traffic island can be widened to decrease the area of paved surfaces, make room for vegetation, and foster social interaction (which currently occurs when given a chance, such as seating units).
- Implementing shade: Due to the low *H*/*W* ratio of this street profile, the canopy structures on the sidewalks should be combined with vertical shading structures to provide shade during the morning and afternoon hours.
- Introducing vegetation: Vegetation in the central traffic island should be interspersed with retractable shading canopies to prevent blocking wind, and trapping longwave radiation and exhaustion fumes under the tree canopies. Likewise, trees and higher shrubs on the sidewalks should be interspersed with retractable canopies (e.g., canvas canopies, louvres, or pergolas). Bare facades fully exposed to direct solar radiation (e.g., side facades projecting higher than the neighboring building) can be covered with climbing plants in raised planters. Flat rooftops can be protected with pergolas and shrubs in raised planters or pots, as long as bearable by the building's structure.

The results of the expert judgments (Table 5) show that P1 artificial scored low, except on affordability, and that P1 nature-based

TABLE 5 Testing results for prototype 3 | wide street N/S-E/W based on scores ranges from 1 to 5.

		Climate-adaptive design	Urban climate	Land use	Equity	Affordability	Mobility	Sense of place
Iteration 1	P1 nature-based	4	2	3	3	3	3	3
	P1 artificial	3	2	2	2	4	2	3
Iteration 2	P2 combined	5	3	5	4	3	4	5

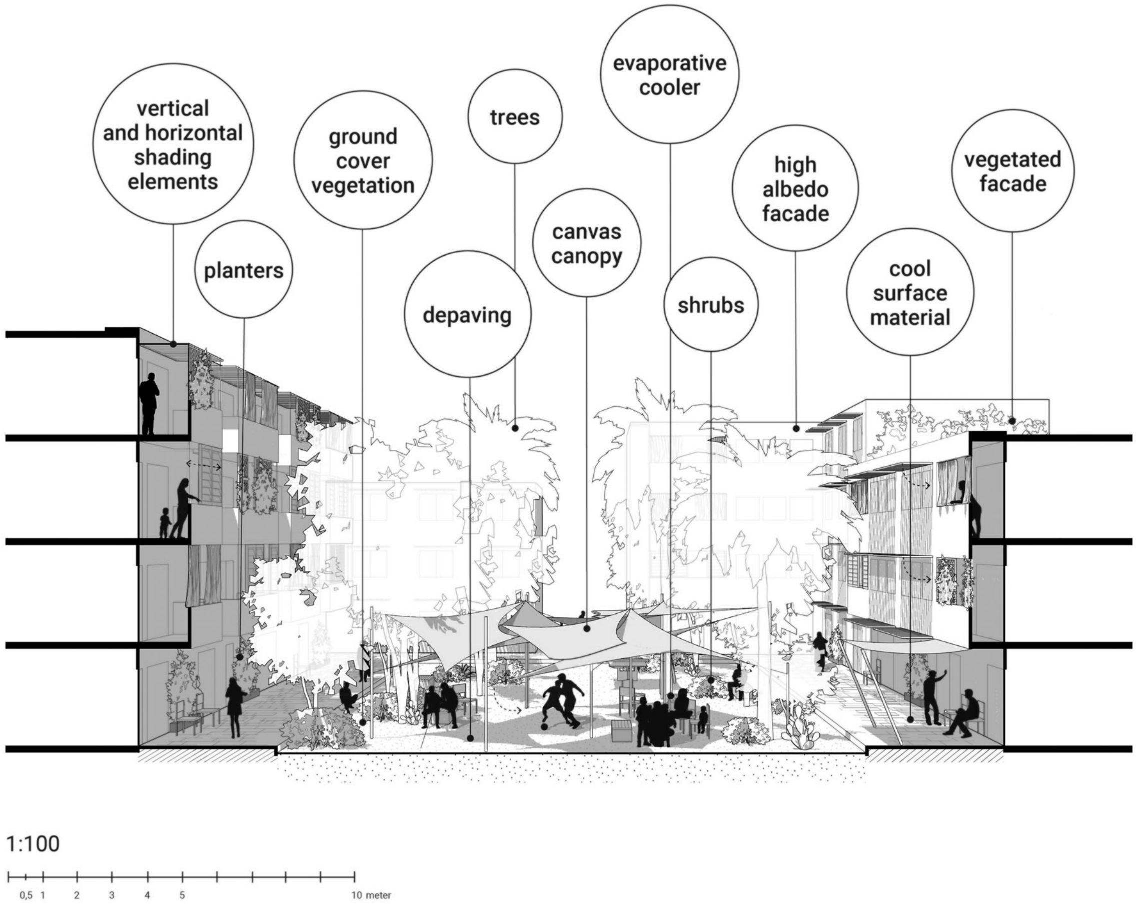

FIGURE 8 Illustration of the design prototype 4 | open space.

scored slightly higher overall. The scores for the combined P2 increased substantially, with most scores falling on 4 (high feasibility) and 5 (very high feasibility). However, urban climate and affordability scored moderate: 3 (feasibility). The match of the interventions included in P3 with the ones proposed in the Ain Shams University workshop (Table 2) indicates the adequacy of the interventions comprised in prototype 3.

3.4 | Prototype 4 | open space N/S–E/W

Prototype 4 (Figure 8) comprises the same interventions as prototypes 2 and 3, although the shape and dimensions of this generic open space, and the absence of car circulation, allow including more and larger interventions from the three groups of climate-adaptive strategies comprised in this study:

- Adapting urban materials: Because these spaces tend not to have intensive car circulation if any at all, depaving can occur to a large extent. Where hard paving is needed, cool surface materials can be used.
- Implementing shade: This prototype comprises the same shading interventions as prototypes 2 and 3, except for the vertical shading structures at the street level proposed in prototype 3.
- Introducing vegetation: Vegetation can be implemented together with retractable canopies to enable natural ventilation and long-wave radiation. Flexibility of use in this space is crucial as it should be suitable for hosting distinct daytime and night-time activities. Urban furniture should be moveable to allow people to meet their thermal comfort requirements, and to foster flexibility of use.

The results of the expert judgments (Table 6) show that the combined P2 interventions scored high: 4 (high feasibility) to 5 (very high

TABLE 6 Testing results for prototype 4 | open space N/S and E/W based on scores ranges from 1 to 5.

		Climate-adaptive design	Urban climate	Land use	Equity	Affordability	Mobility	Sense of place
Iteration 1	P1 nature-based	5	3	3	3	4	4	3
	P1 artificial	3	3	1	4	4	2	3
Iteration 2	P2 combined	5	5	5	4	3	5	5

feasibility), with affordability being the only exception: 3 (feasibility). The results of T2 show, thus, that this is a feasible prototype given all criteria considered. Furthermore, the match between the interventions included in P3 with those proposed in the Ain Shams University workshop (Table 2) indicates the adequacy of the interventions comprising prototype 4.

4 | DISCUSSION

This section discusses how the criteria considered in this study are addressed (or not) by each prototype, and which challenges remain.

4.1 | Climate-adaptive design and urban climate

Because this study is focused on informal urban areas, it is important to reflect not only on the likely effectiveness of the prototypes in reducing heat stress, but also on the opportunities and challenges posed to this effectiveness in informal urban areas.

All prototypes include increasing albedo and/or adapting specific heat properties of urban materials as this can effectively decrease local ambient temperatures by increasing reflectivity and permeability, and reducing heat storage (Farhadi et al., 2019; Mills et al., 2021). While increasing albedo by re-coloring outdoor surfaces can be easily implemented by local authorities or even residents, installing cool surfaces can be more challenging as it deals with more structural and costly interventions. Next to this, the function of a street can limit these interventions. For example, Prototype 3 scored relatively low (3: feasibility) on urban climate compared to the remaining criteria because there are more hard-paved surfaces than in other prototypes, which has to do with mobility needs.

Shading by artificial vertical and horizontal structures is proposed in all prototypes as means to decrease air temperature and radiant heat (La Roche et al., 2020). All shading elements are flexible so users can regulate them according to their thermal comfort requirements (Nikolopoulou & Steemers, 2003) throughout the day and seasons. All shading interventions echo local building practices, hence holding the potential to contribute to equity and sense of place, be affordable, and easily implemented by locals (e.g., canopies made of palm leaves). Colonnades were not included in the prototypes as this type of structures ended up being considered less affordable, and may impair mobility and wind flow in the narrower streets.

Regarding the introduction of vegetation, while their cooling effects are widely described in the literature (e.g., Dihkan et al., 2021; Klemm, 2018; Schlaepfer et al., 2020), employing vegetation in informal areas in hot arid climates comes with challenges. First, planting trees and shrubs might be largely conditioned or even impaired in narrow street profiles due to lack of space. Second, the predominance of motorized traffic can endanger plants' survival or healthy growth. Finally, due to high solar radiation and limited water availability, plants in hot arid climates minimize the amount of moisture released throughout the day compared to vegetation growing in climate types such as the temperate, which leads to lower evaporative cooling potential (Feyisa et al., 2014). The lower scores (3: feasibility) given on affordability for Prototypes 2 and 3 are partly due to acquisition costs, but largely due to maintenance costs from irrigation needs. Using species adapted to hot arid climates and/or that have high heat and drought tolerance (e.g., *Olea europaea*, *Plumeria alba*, or *Hyphaene thebaica*) can be an answer to this challenge. Another possible solution is to implement water-sensitive urban planning and design strategies to maximize available water resources while also generating additional community well-being and ecological benefits (Negev et al., 2020).

4.2 | Land use planning

The testing of the prototypes shows that they hold the potential to act as a catalyst to improve the spatial and social assets within informal urban areas. This approach is relevant when the informal actors and institutions control the land and markets are shaped by insufficient formalized land and housing, inadequate legal frameworks and excessive regulations, and costly or difficult formalization/regularization processes.

Jacobs (1961) defines social capital as "the web of relationships and cooperative action between people who share a geographic space in big cities and an interest in maintaining a healthy neighbourhood." Established networks of small-scale, everyday public life and urban self-governance emerge from these relationships over time. Shubra is a self-governing area, and the design interventions comprised in the prototypes aim to empower a self-governing capacity for urban and social resilience. These interventions address thermal comfort thresholds for different ages, genders, and vulnerable groups to create healthy and inclusive outdoor urban spaces. In this regard, the prototypes include interventions that can aid in optimizing land use investment, fostering benefits of living in agglomeration, improving security and land access, and reducing the strain on infrastructure provision. Additionally, the prototypes can increase the value of informal land, which are often threatened by urban redevelopment projects (Gómez-Villarino & Ruiz-Garcia, 2021).

4.3 | Equity

Most of the prototypes score well in terms of equity, ranging from feasible to very feasible (3–5). Due to the multifaceted nature of equity in this context, the results are based on a combination of considerations and trade-offs that affect the equity of the proposed interventions. In the context of our study, the following aspects are particularly relevant.

First, the absence of formal regulatory frameworks in the study area precludes a complete equity assessment, due to the absence of formalized norms and processes that ensure equity. The meaning of equity within this context, or any other regulatory context, tends to be underpinned by a set of formal principles that guide the legislator in the design and implementation of the law (Zeben, & Rowell, 2020). This often includes fundamental safeguards traditionally set out in human rights-related documents or national constitution. These principles and rights, contextualized by court judgments applying them to specific circumstances, express the normative content of equity in specific, often national, regulatory contexts. Informal settlements exist within the national jurisdiction of a nation-state. However, as their development and management can take place outside the control of formal national institutions, the safeguarding of equity is complicated both because the settlements are not developed with this particular contextualized definition of equity in mind, and because enforcing such concepts afterwards can be practically difficult.

Second, even if we apply the relevant national equity standards to our informal settlement, this 'standard' of equity can be contested by the inhabitants of the informal settlements. As these inhabitants are often politically and socially marginalized, it is likely that their interests were not represented in formal participation processes and that the formal legal and political framework does not meaningfully or equitably incorporate their interests (e.g., Sedky, 2000).

Third, there is a procedural dimension to equity: while the presence of these measures tends to be welfare- and equity improving, the process of selecting and adopting them also matters for overall equity. Public participation and consultation are key, but often require a robust regulatory framework that can be lacking in informal settlements or may exclude the inhabitants of informal settlements.

Keeping these considerations in mind, the prototypes that performed well from an equity perspective were those that allowed for an overall improvement of residents' health and well-being due to lowering of temperature, and general livability without reducing economic capabilities (e.g., by reduced access to shops and/or reduced opportunities to commute to places of employment) and without prioritizing the needs and capabilities of some residents over others. The co-benefit and multifunctionality of vegetation-based interventions are especially important for the latter, as economic, social and ecological benefits of the measures should be able to foster resilience amongst the entire population of the settlement.

A final challenge is the prioritization of climate resilience as compared to other basic needs of residents of informal settlements. Medium- to long-term investments in climate resilience can significantly improve health, well-being, or livability. However, these improvements may be seen as secondary—including by residents themselves—to immediate concerns related to economic development, social mobility, and safety. Under conditions of resource scarcity, this prioritization may delay the adoption of the proposed interventions, even if these interventions would have a positive effect on other vectors of well-being as well.

4.4 | Affordability

All prototypes generally scored highly in affordability (from 3 to 5). Questions of affordability and (financial) capacity are long-standing in the literature regarding the upgrading of informal urban areas (e.g., Muchadenyika & Waiswa, 2018; Mutero & Chege, 2019). We appraised relative affordability based on four factors: upfront versus ongoing costs (e.g., capital expenditures versus maintenance costs), the source and availability of capital, the distribution of costs (and benefits), and questions of ownership (e.g., individual versus collective control and responsibility for paying for adaptation). Given the exploratory nature of this study and the geographical and multilevel stakeholder specificities at play, these appraisals were high-level and qualitative, serving to spark a discussion about how economic constraints may determine the feasibility and implementation of the prototypes.

First, the design process should consider the upfront and ongoing costs of interventions. While some interventions (e.g., depaving) may have low upfront costs, ongoing expenses may be too high for residents, raising durability and sustainability questions. On the other hand, more structural interventions (e.g., street shading canopies) are likely to have substantially higher upfront costs, but may be relatively inexpensive to maintain over time. In addition to factoring in calculable hard costs (e.g., replanting), it is also important to consider potential transactional (social) costs associated with maintaining interventions without clear ownership or accountability (a point which we considered concerning questions of ownership).

Second, the source and availability of capital for improvements is a major consideration that shapes the feasibility of certain interventions and their relative costs to the community. Multilateral development institutions (e.g., the World Bank), national and sub-national agencies, and quasi-governmental agencies may have funding mechanisms that can offset some or all of the costs of specific interventions, above and beyond individual or community self-organized funding schemes, for example. Assessing these multilevel institutional resources and funding opportunities up front can help to guide conversations about which types of interventions are most economically feasible.

Third, it is crucial to consider how costs (and benefits) are distributed over other social criteria, such as the costs and benefits to residents versus commercial stakeholders. While interventions like widening pavements and adding vegetation provide costs and benefits to residents, these interventions could, for example, limit motorized traffic and thereby create concerns about negative impacts to certain incumbent businesses. Similarly, while redesigned areas can provide economic benefits such as increased room for street vendors, these improvements may become more popular and, by extension, valuable. It is worth considering if this would lead to commercial displacement risks and how these might be addressed in ways that maintain neighborhood accessibility for those with the least economic means, or who may be marginalized along other social lines. Awareness of these multifaceted distributional concerns is key when adapting the prototypes to local circumstances.

Fourth and finally, questions of ownership are vital: who is responsible for interventions, and who assumes their costs and benefits? On the one hand, this is a legal-technical question that may be important when accessing financial resources for interventions from institutional sources. On the other hand, ownership also relates to a broader question of responsibility. How do communities build and maintain consensus about the selection and maintenance interventions, with the costs and benefits fairly distributed over time? A range of institutional forms, from grassroots community associations to multilevel local or regional settlement upgrading institutions, may play key roles in mediating debate over such questions. While it is difficult to distil these relational variables into quantitative scores without deeper local knowledge, the RTD expert judgments prompted reflection about the diverse and intersecting criteria that can co-determine affordability as a design consideration. This mindset should encourage designers to weigh multiple affordability factors when devising climate-adaptive design interventions in informal urban areas.

4.5 | Mobility

The prototypes comprise the creation of spaces for traffic flow, parking, and social interaction. Within the informal settlements common to urbanized Africa, streets fulfill multiple mobility functions (Kita et al., 2020). This is true for all street profiles identified, especially the narrower ones, which are utilized for the movement of people and goods, while also functioning as public spaces where activities from the home or shops can spill over. The removal of motorized traffic was pondered but eventually discarded. Public transportation offer in Cairo is poor (i.e., insufficient or infrequent service, and long journey times), reason why the experts on local cultural advised against the complete removal of car circulation as this would most likely be rejected by local communities. The alternative was to create pedestrian- and bicycle-oriented prototypes, as described below.

With this in mind, the first challenge for mobility is arguably that most informal urban areas need a clear hierarchy of streets and traffic speed, as failing to do so can create negative perceptions of safety, and can cause congestion (Hidayati et al., 2020). The prototypes propose a more explicit hierarchy of streets in relation to different types of traffic. For example, in Prototype 1 the type of paving and shading devices is meant to encourage pedestrians to walk and interact, while the paving of motorized circulation zones is more uneven to discourage high traffic speeds. Prototypes 2 and 3 comprise areas for demarcated motorized traffic, and are interspersed with calming traffic measures (e.g., parking bays or vegetation pockets) for a more efficient traffic flow and increased pedestrian safety. All design interventions aim at contributing to the safety and engagement of socially vulnerable groups (e.g., visually impaired or people in wheelchairs). For example, pedestrian zones include even ground surfacing and traffic calming measures that enable the elderly to safely engage in outdoor social experiences beyond the current (narrow) sidewalks.

The second challenge might be to balance efficient traffic flow and liveable public spaces. For example, in Prototype 4 the introduction of public seating areas, playground infrastructure, and vegetation creates an open public space between buildings that encourages pedestrian mobility and social encounters throughout the day and night. Likewise, the widened and planted traffic island in Prototype 3 reduces traffic lanes and provides a place for pedestrians to rest, which is particularly beneficial for older adults.

Tailoring the prototypes to a site requires knowing the residents' everyday mobility practices, through co-creation or observation. This allows identifying the most used routes and, thereby, the planning of a hierarchy of roads and public spaces that improve general mobility (Oviedo et al., 2021). In addition, coordination efforts beyond the intervention site(s) are required to ensure the functioning of the city-wide mobility network.

4.6 | Sense of place

Urban informal settlements are frequently treated as being outside of 'normal' urban considerations, leading to their residents' discrimination, eviction, and displacement (Lombard, 2014). However, in addition to reducing the impacts of climate stresses and shocks in urban areas, climate-adaptive spatial interventions incorporating locals and their know-how can aid in revitalizing the social life of informal urban areas.

The Ain Shams University workshop indicated that interventions that respond to the socio-cultural context can have higher feasibility – designing with people who know the local cultural needs and traditions can benefit a sense of place, place identity, and social cohesion. This may increase the likelihood of climate-adaptive design interventions to be implemented and nourished. These are aspects related to Norberg-Schulz's (1979) Genius Loci concept: the meanings, identity and memories of a place.

The workshop and the testing of the prototypes offered insights that echo some of the ideas Scott (1998) posited on urban development and society. First, the potential that developing small-scale interventions, standing back, observing, and then planning the next small-scale intervention holds in defining the effectiveness of interventions. Second, the process underscored the significance of implementing interventions that can easily be undone if they do not perform as expected, or fail. Third, the importance of developing interventions that allow the most extensive accommodation possible to the unforeseen (e.g., the uncertainty intrinsic to future climate projections). Last, the study unearthed opportunities to develop interventions that account for the capability of those involved in a project to have, or to have later, the experience and insight required to maintain or even improve the design schema.

4.7 | Limitations

This study is a conceptual and exploratory study primarily focused on urban climate-adaptive design. Our goal was not to provide an in-depth investigation on the feasibility topics addressed, although this may had been crucial for further refinement. We focus on climate-adaptiveness and reflect about the interventions developed in light of those feasibility topics.

Because few studies have been dedicated to climate-adaptive design in Egyptian cities, more abundant information on this topic could have led to different design interventions. Next, the lack of meteorological observations and the research timeframe made it difficult to address heat stress quantitatively.

The Ain Shams University workshop aimed provided a preliminary way to validate initial design studies through a local stakeholder lens. However, looking forward, a robust co-production process with residents would be essential to better understand how the design interventions could meet local needs, foster equity or spark deeper resident engagement.

5 | CONCLUSION

This is a conceptual and exploratory interdisciplinary research study that investigates feasible climate-adaptive spatial design interventions in high-density informal urban areas in hot arid climates from a multidisciplinary perspective. The aim is to inform about streetscape interventions that address heat stress in these areas. The conceptual approach proposed is more holistic than previous studies on climate-adaptive design in hot arid climates, and focusses on urban settlements not commonly tackled in climate-adaptive design studies. The use of RTD in developing this approach is also of relevance.

Our findings indicate that there is room to implement climate-adaptive design strategies in informal urban areas in hot arid climates, but also that these might face some feasibility challenges. Common climate-adaptive design strategies can be used to address heat stress in these areas. Adapting urban materials can be an effective strategy but also present challenges in affordability and mobility terms. Implementing shade can also be effective, affordable (low-cost interventions), benefit equity (engagement of different sectors of the population) and sense of place (connection to traditional building practices). Introducing vegetation holds the potential to be highly effective regarding cooling effects which, however, may be undermined should plants die or in case of leaf loss during heat and drought periods. In this case, water irrigation needs might also become a liability (affordability). Finally, increasing vegetation should match local movement patterns as to ensure their upkeep and match mobility needs.

The findings of this study and the discussion points raised above call for further research on place-embedded and quantitative testing of the effects of the prototypes. The opportunities discussed for each feasibility criteria may contribute to sustainable development goals, but these links need to be solidified when the proposed interventions are further studied within particular contexts, and through the integration of further input of local communities. Likewise, it is important that future research includes residents in the co-design and refinement of the prototypes and/or in developing new insights on the topic. Finally, an in-depth look at how vernacular building practices and elements can increase the impact and (technical and socio-cultural) feasibility of the design interventions proposed would be particularly relevant.

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