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Integrated Airflow Systems in Enclosed Courtyards: Typologies and Scientific Dynamics

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Research Article

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Abstract

This paper investigates dynamic airflow patterns within enclosed courtyard spaces, with particular focus on traditional Cairene residential architecture in the hot-arid climate of Cairo. These buildings exemplify centuries of climate-responsive design, where passive strategies—compact layouts, thick walls, and inward-facing courtyards—were employed to optimise thermal comfort and natural ventilation. The study examines how geometric parameters, including courtyard proportions, sectional aspect ratios (SAR), and building orientations, shape airflow behaviour. By analysing solar exposure across multiple case studies, three principal airflow typologies are identified: (1) the courtyard as a cool reservoir enabling cross-ventilation driven by pressure differentials; (2) a thermal updraft exhaust system, where solar-heated surfaces generate stack-effect convection; and (3) interconnected courtyards producing gradient-induced flow through intermediate transitional spaces such as the takhtabush. Solar radiation simulations reveal that courtyard floors receive peak cumulative radiation of approximately 2.8 kW/m², generating the buoyancy forces that sustain passive ventilation cycles. The findings offer practical design guidance for climate-sensitive architectural interventions in dense urban environments, demonstrating that systematic calibration of courtyard geometry can substantially improve indoor ventilation performance without mechanical systems.

1 Introduction

Courtyard architecture represents one of the most enduring responses to climatic adversity in the built environment. Across arid and semi-arid regions, the inward-facing courtyard has functioned simultaneously as a spatial organiser, a social nucleus, and an environmental regulator—channelling light, moderating temperature, and directing airflow through purely passive means. In the dense urban fabric of Islamic Cairo, this typology reached a particular refinement, producing a body of residential architecture that remains instructive for contemporary sustainable design.

Despite the growing body of simulation-based research on courtyard thermal performance, the specific airflow mechanisms operative in enclosed Cairene courtyards remain incompletely systematised. Most existing studies focus on geometric parameters in isolation [1, 2, 5] or on broader regional comparisons [3, 7], without integrating morphological analysis with solar radiation data to produce a typological classification of airflow regimes. This study addresses that gap.

The present paper makes three contributions. First, it provides a systematic geometric and morphological analysis of traditional Cairene courtyard houses, identifying the orientations, plan configurations, and aspect ratios characteristic of the building stock. Second, it reports solar radiation simulations that quantify the thermal drivers of airflow within these enclosed spaces. Third, it proposes a three-typology classification of courtyard airflow patterns, each grounded in identifiable thermodynamic principles and supported by historical case-study evidence.

2 Background and Literature Review

2.1 Thermal Performance of Courtyard Architecture

Courtyard architecture demonstrates heightened energy efficiency in hot-dry and warm-humid climates [1]. Simulation-based studies have consistently validated the effectiveness of enclosed courtyards in improving indoor and outdoor thermal comfort in arid contexts [6, 8, 9]. In warm-humid climates, design priorities shift toward continuous natural ventilation, solar protection, and mitigation of daytime heat accumulation [12]. Critical design parameters—courtyard geometry, window-to-wall ratio, and building orientation—significantly influence thermal performance, as demonstrated through CFD and multi-objective optimisation studies [2, 7, 9, 14].

Rectangular courtyards with a 1:2 length-to-width ratio improve air velocity and cooling compared with square layouts, although square courtyards offer reduced solar heat gain—an advantage in humid climates [2, 5]. Aspect ratios between 0.7 and 1.0 enhance natural airflow through vortex formation [4], while northeast–southwest or east–west orientations yield better thermal conditions [3]. Incorporating cross-ventilation strategies between paired courtyards further reduces overheating [9].

2.2 Airflow Dynamics in Courtyards

Airflow within courtyards is governed by four interacting mechanisms: wind entry and re-circulation, buoyancy-driven ventilation, courtyard geometry, and interaction with surrounding built elements [6, 8].

Wind typically enters through open sides or architectural gaps, producing flow separation and re-circulation zones in enclosed typologies. These dynamics generate corner vortices and downwash effects that reduce ventilation efficiency at lower levels [4, 6]. Buoyancy-driven ventilation—the stack effect—contributes substantially when solar radiation heats courtyard surfaces, creating temperature gradients between sunlit and shaded zones. This stratification produces vertical airflow and localised pressure differences that can either enhance or hinder overall ventilation depending on courtyard openness and orientation [5, 8].

The geometry of the courtyard—particularly the SAR (height/width), plan shape, and opening orientation—profoundly influences airflow behaviour. Courtyards with high SAR values exhibit stagnation zones at lower levels due to inadequate wind penetration [1, 2], whereas shallow courtyards allow better cross-ventilation. Mohsen [13] demonstrated that deep courtyards (SAR > 1.3) predominate near 30°N latitude precisely because limiting solar penetration is the primary design imperative. For lower latitudes with warm-humid climates, shallow courts prevail to facilitate wind-driven ventilation.

The courtyard's interaction with surrounding built elements further modulates airflow through windward and leeward pressure zones [7]. In dense urban contexts such as historic Cairo, the urban canyon effect channels wind along narrow alleys and into courtyard voids, providing a supplementary ventilation mechanism independent of direct wind exposure [11].

2.3 Traditional Cairene Architecture and the Courtyard

Traditional Cairene residential architecture, spanning the late Mamluk period (1259–1517) through the Ottoman period (1517–1805), represents a highly evolved response to Cairo's hot-arid climate: low annual rainfall, near-constant sunshine, and prevailing northwest and northeast winds [10]. The interior courtyard functioned as the heart of the dwelling, organising spatial circulation, admitting light and ventilation, and regulating the thermal environment through a combination of proportions, shading, water features, and vegetation.

The courtyard was surrounded by key architectural elements—the iwan (vaulted hall), maq'ad (elevated open-air sitting area), and takhtabush (shaded transitional space)—each strategically positioned to exploit seasonal airflow patterns [10]. Wind catchers (malqafs), integrated into upper building corners, captured northern breezes and directed them into interior rooms [11]. The projection of south-facing wall overhangs controlled solar radiation loads in summer, following principles described by Mohsen [13].

The orientation of Cairene courtyards typically varies within ± 30° of true north, reflecting a balance between the irregular urban street grid and sensitivity to the solar path and prevailing winds [10]. The majority adopt a square or near-square plan, producing even solar exposure and thermal balance across internal façades. Elongated courtyards, where they occur, are predominantly aligned along the north–south axis, maximising stack-effect performance [2, 5].

3 Methodology

This study adopts a systematic analytical framework to investigate the geometric, morphological, and environmental characteristics of courtyard spaces in traditional Cairene buildings. The research design comprises four sequential stages: case selection and data collection; geometric and morphological analysis; sunlight exposure analysis; and solar radiation simulation.

3.1 Case Selection

A selection of courtyard-based architectural examples was compiled from historical Cairene residences, chosen to represent diversity in spatial configuration, orientation, and courtyard proportions. All selected buildings incorporate complementary passive cooling strategies—wind catchers, takhtabush spaces, mashrabiyya screens, vegetation, and water features—making them suitable for comprehensive environmental analysis.

3.2 Geometric and Morphological Analysis

Each case study was systematically analysed to extract: (i) courtyard orientation relative to cardinal directions; (ii) plan configuration (square, rectangular, or elongated); (iii) SAR (height/narrowest width) following the convention of Mohsen [13]; and (iv) courtyard complexity, distinguishing single from interconnected multiple courtyards. This allowed comparative assessment of how different spatial arrangements support or inhibit airflow and thermal comfort.

3.3 Sunlight Exposure Analysis

Sunlight hour simulations were conducted to assess the duration and distribution of solar exposure throughout the day, identify façades and surfaces receiving the highest solar input, and evaluate shading contributions from overhangs, adjacent structures, and vegetation. This stage identified solar-driven microclimatic zones within each courtyard and supported the subsequent categorisation of heat accumulation and shading effects.

3.4 Solar Radiation Analysis

Daily solar radiation simulations quantified total solar radiation (kWh/m²) received on courtyard floors and walls, providing the thermal loading data that drives vertical convection and pressure gradients, and assessed each courtyard's capacity to dissipate or absorb heat across the diurnal cycle. Together, the sunlight exposure and radiation analyses informed the typological classification presented in the Discussion.

4 Results

4.1 Geometric Findings

4.1.1 Orientation

Cairene courtyards exhibit orientations typically within ± 30° of true north. This limited angular range reflects a design sensitivity to both solar path and prevailing wind conditions. Although fully enclosed courtyards are not directly exposed to prevailing breezes, this orientation controls the solar exposure pattern on internal façades throughout the day.

4.1.2 Plan Configuration

The majority of analysed courtyards adopt a square or near-square plan form. This compact geometry is spatially efficient within dense urban fabric and produces uniform solar exposure and thermal balance across internal façades. Elongated courtyards, found predominantly in larger or irregularly plotted houses, are almost exclusively aligned along the north–south axis, maximising stack-effect performance [2, 5].

4.1.3 Sectional Aspect Ratio

At Cairo's latitude of approximately 30°N, the sun follows a high summer arc from northeast to northwest and a lower winter arc from southeast to southwest. Narrow, deep courtyards (high SAR) restrict sunlight penetration—advantageous in summer for shading but limiting in winter for solar heating. Shallow courtyards (low SAR) allow greater winter sun penetration but risk excessive solar gain in summer. Moderate SAR values broadly consistent with the 0.7–1.0 range [4, 3] balance these competing requirements in the Cairo context.

Daily solar radiation simulations quantified total solar radiation (kWh/m²) received on courtyard floors and walls

4.2 Solar Radiation and Sunlight Results

4.2.1 Floor Exposure and Thermal Mass

The courtyard floor is exposed to the highest solar radiation levels of any surface, with peak cumulative values reaching approximately 2.8 kW/m² between 09:00 and 15:00. This intense gain transforms the floor into a major thermal mass, generating a vertical temperature gradient. The resulting buoyancy-driven air movement produces natural convection currents that sustain the passive ventilation cycle.

4.2.2 Wall Exposure and Suction Potential

Inner walls facing south, southeast, and southwest receive cumulative peak radiation of approximately 1.7 kW/m². As these surfaces heat the adjacent air column, upward convective movement reduces pressure near the wall base, generating a suction effect that draws cooler air from shaded interior spaces into the courtyard. This mechanism underpins the thermal updraft exhaust typology described below.

4.2.3 Thermal Stratification

The combined solar input on floor and wall surfaces produces a stratified thermal environment: hotter air accumulates near sun-exposed surfaces, while cooler air persists in shaded or interior zones. This stratification sustains a natural ventilation cycle when the courtyard is equipped with high-level openings or stack elements such as malqafs. Excessive floor radiation without adequate shading or escape routes may, however, cause heat entrapment that diminishes comfort.

5 Discussion

5.1 Typological Classification of Courtyard Airflow Patterns

The geometric and environmental analyses identify three discrete airflow typologies in traditional Cairene courtyards, each governed by a distinct thermodynamic mechanism. Taken together they constitute a design vocabulary that allows practitioners to diagnose the dominant ventilation mode in a given building and to calibrate spatial interventions accordingly, summarised in Table 1.

Table 5
Typological classification of courtyard airflow patterns in traditional Cairene architecture

Type	Primary Driver	Key Element(s)	Mechanism	Principle
1. Cool Reservoir / Cross Ventilation	Wind pressure + minor buoyancy	Low & high openings; shaded courtyard	Cool courtyard air enters low; warm air exits high	Pressure differential; density-driven flow
2. Thermal Updraft Exhaust	Stack effect (solar-heated wall)	SE-facing thermal mass wall; malqaf	Hot air rises along wall; suction draws cool air in	Chimney effect; solar buoyancy
3. Interconnected Courtyards (Gradient Flow)	Temperature differential between courtyards	Two courtyards (shaded + sunlit); takhtabush	Rising hot air in sunny court pulls cool air through passage	Bernoulli's principle; thermal buoyancy

5.1.1 Typology 1: Courtyard as a Cool Reservoir (Cross Ventilation)

The courtyard functions as a thermal sink whose shaded and vegetated interior remains cooler than adjacent indoor spaces. Cool, denser air is drawn into rooms through strategically placed lower openings, while warmer indoor air is expelled through higher-level openings on opposite façades, facilitating cross ventilation. The driving mechanism combines pressure differentials between windward and leeward sides of the building with density differences between the cool courtyard air and warmer indoor air [6, 8]. This typology is most effective in courtyards with square or near-square plan configurations where uniform shading is achievable, and in buildings where openings are located at multiple levels.

5.1.2 Typology 2: Thermal Updraft Exhaust System

A southeast-facing thermal mass wall absorbs solar radiation (peak ~ 1.7 kW/m² on south and southeast surfaces) and heats the adjacent air column, generating an updraft that creates a negative-pressure zone at courtyard base level [1, 13]. Cooler interior air is drawn in to replace it, establishing a convective loop. The courtyard floor amplifies this effect: with peak radiation reaching ~ 2.8 kW/m², the heated air mass rising from the floor reinforces buoyancy and increases the rate of air recruitment from interior spaces [7, 14]. Where a malqaf is present it superimposes a wind-driven component, materially increasing ventilation rates. The critical failure mode is heat entrapment — warm air recirculating within a closed volume when high-level exhaust routes are absent — which explains the consistent provision of wind catchers and upper-level openings across the historic building stock.

5.1.3 Typology 3: Interconnected Courtyards with Thermal Gradient Flow

In multi-courtyard houses, a thermally differentiated pair of spaces — one sunlit and paved, one shaded and planted — drives a sustained pressure-differential flow through the connecting transitional element, typically the takhtabush [10]. At Bayt Al-Suhaymi, the takhtabush is open to the heated outer courtyard on one side and linked to the cooler inner garden via a mashrabiyya on the other; as the outer courtyard heats and its air rises, cooler garden air is drawn through continuously. The mashrabiyya controls velocity and introduces evaporative cooling from the planting, adding a humidity benefit to the pressure-driven draught. The system operates on both diurnal drives: solar gain during the day and nocturnal cool-air descent at night [10, 12].

5.2 Design Implications

The three typologies identified are not mutually exclusive; historical Cairene houses frequently combine elements of all three within a single building. The classification is nonetheless analytically useful: it allows designers to identify which mechanism is primary in a given spatial configuration and to strengthen it through targeted interventions. For Typology 1, the critical variables are the relative positioning and sizing of low and high openings and the degree of courtyard shading. For Typology 2, the orientation, material thermal mass, and height of the thermally active wall are the primary design handles. For Typology 3, the spatial relationship between thermally differentiated outdoor spaces and the cross-sectional properties of the connecting transitional element are determinative.

These findings support and extend the body of literature demonstrating that courtyard geometry is the primary lever of passive ventilation performance [1, 7, 14], while also contextualising the general principles within the specific urban morphology and architectural vocabulary of Islamic Cairo. The characteristically high SAR values of Cairene courtyards—which diverge from the 0.7–1.0 optimum identified for humid climates [4]—are explicable as a rational response to Cairo's dominant summer overheating problem, in which shading consistently outweighs the competing demand for ventilation access.

6 Conclusion

This study has presented a systematic analysis of airflow dynamics in traditional Cairene courtyard architecture, integrating geometric and morphological analysis with solar radiation simulation to produce a three-typology classification of passive ventilation mechanisms.

The first typology—the cool reservoir—relies on pressure and density differentials to drive cross ventilation between a shaded courtyard and adjacent rooms. The second—the thermal updraft exhaust—harnesses solar-heated wall surfaces and the stack effect to generate continuous convective airflow, amplified where malqafs are present. The third—interconnected courtyard gradient flow—exploits thermal differentiation between paired outdoor spaces connected by a takhtabush to produce a self-sustaining breeze. All three are grounded in identifiable thermodynamic principles and are expressed with particular refinement in the Mamluk and Ottoman residential fabric of Cairo.

Solar radiation simulations confirm that courtyard floors, reaching peak cumulative radiation of approximately 2.8 kW/m², function as the primary thermal engine of buoyancy-driven ventilation. South-southeast wall surfaces, receiving approximately 1.7 kW/m², provide a complementary suction mechanism. Optimal performance requires both adequate thermal mass to moderate heat release and sufficient high-level openings or stack elements to permit the escape of warm air.

The findings have direct implications for the sustainable design and adaptive reuse of courtyard buildings in hot-arid urban environments. The typological framework allows practitioners to diagnose the dominant airflow mechanism in a given building, identify limiting conditions, and prescribe targeted geometric or material interventions. Future work should extend the simulation base to validated CFD modelling across the full diurnal and seasonal cycle, and should develop quantitative performance thresholds for each typology to support evidence-based design guidance.

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Figures

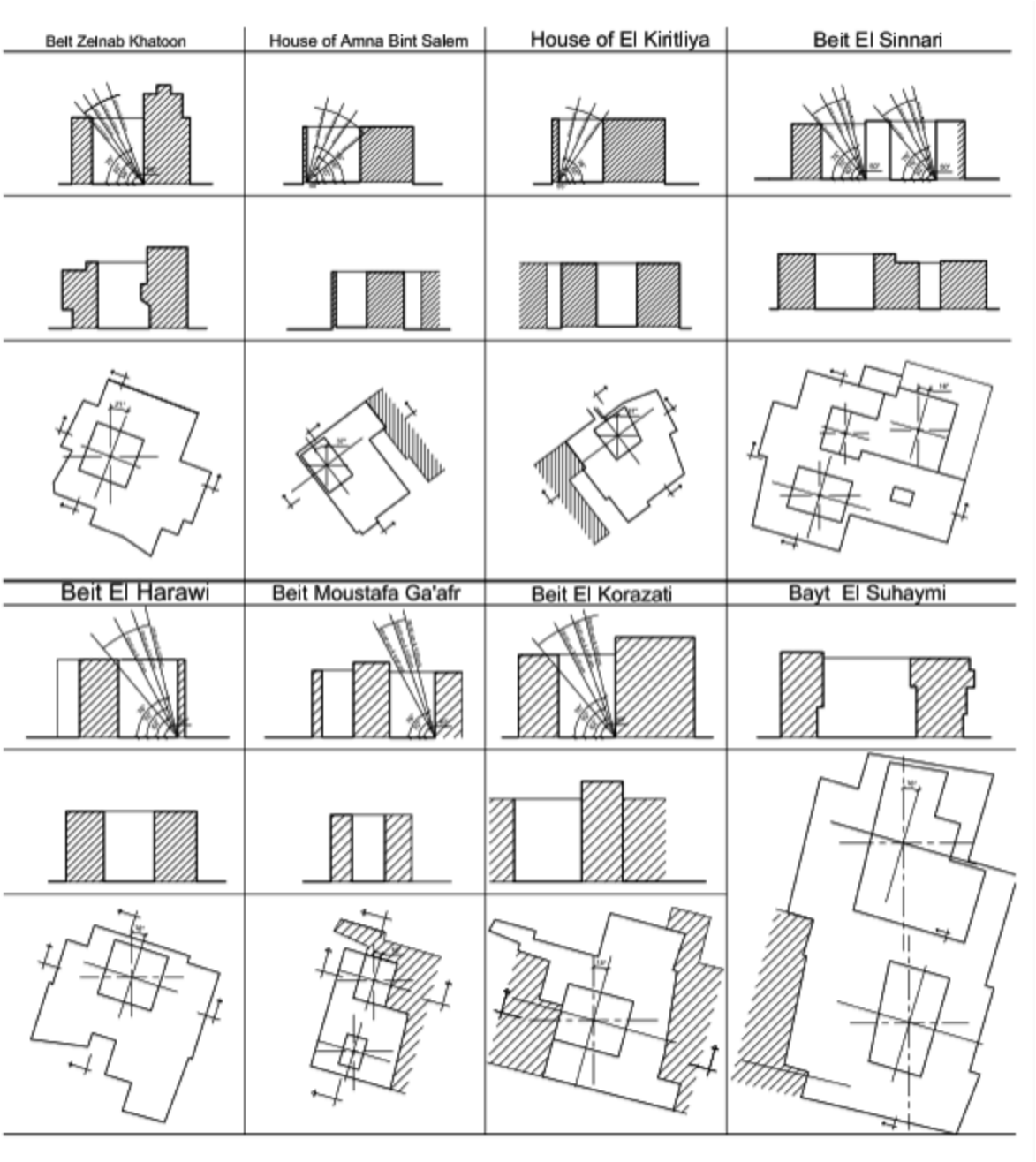


Figure 1

Diagrammatic plans and sections showing courtyard orientation and aspect ratio for eight traditional Cairene houses

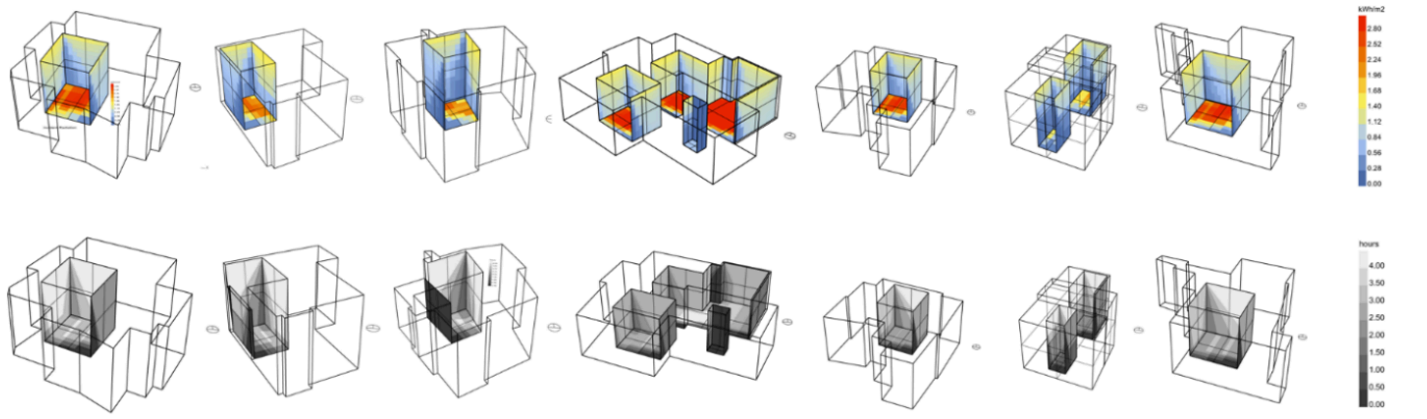


Figure 2

3. Daily solar radiation simulations & Sunlight Hours quantified total solar radiation (kWh/m²) received on courtyard floors and walls.

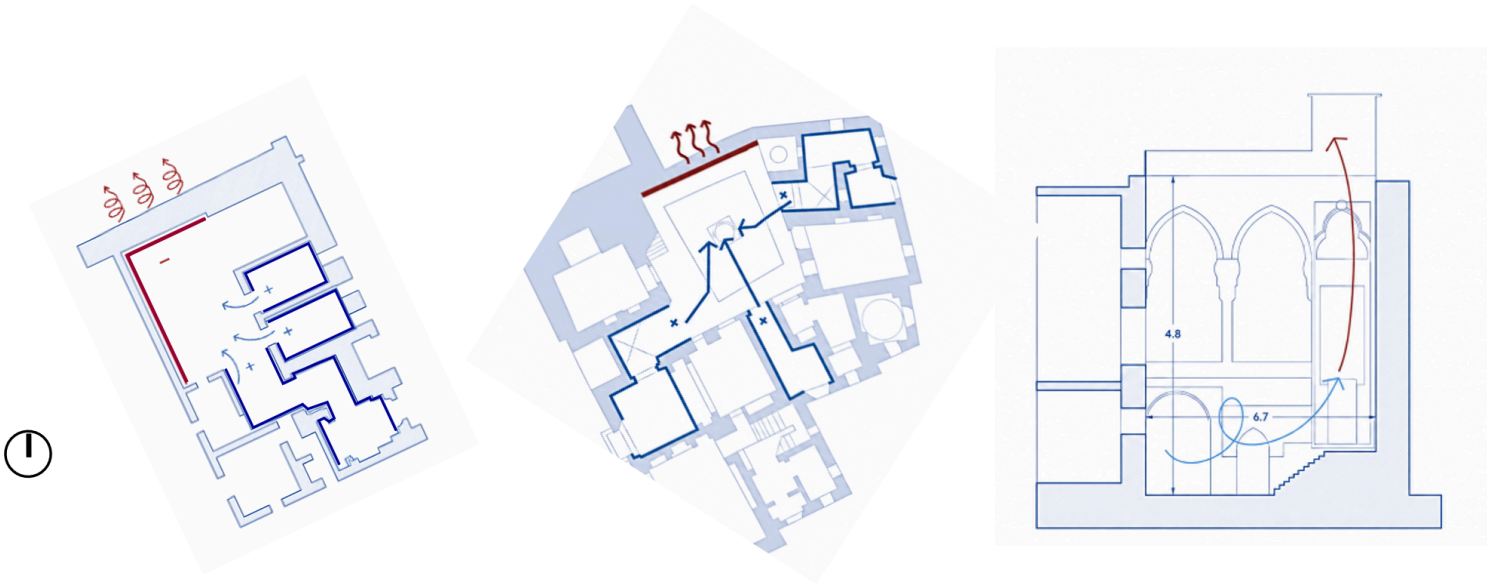


Figure 3

4. Airflow diagrams for Beit Amna Bint Salem and Beit Al-Kiritliya, showing thermal updraft and cross-ventilation patterns: ground-floor plan (left) with airflow paths, and section through the qa'a (right) indicating convective circulation

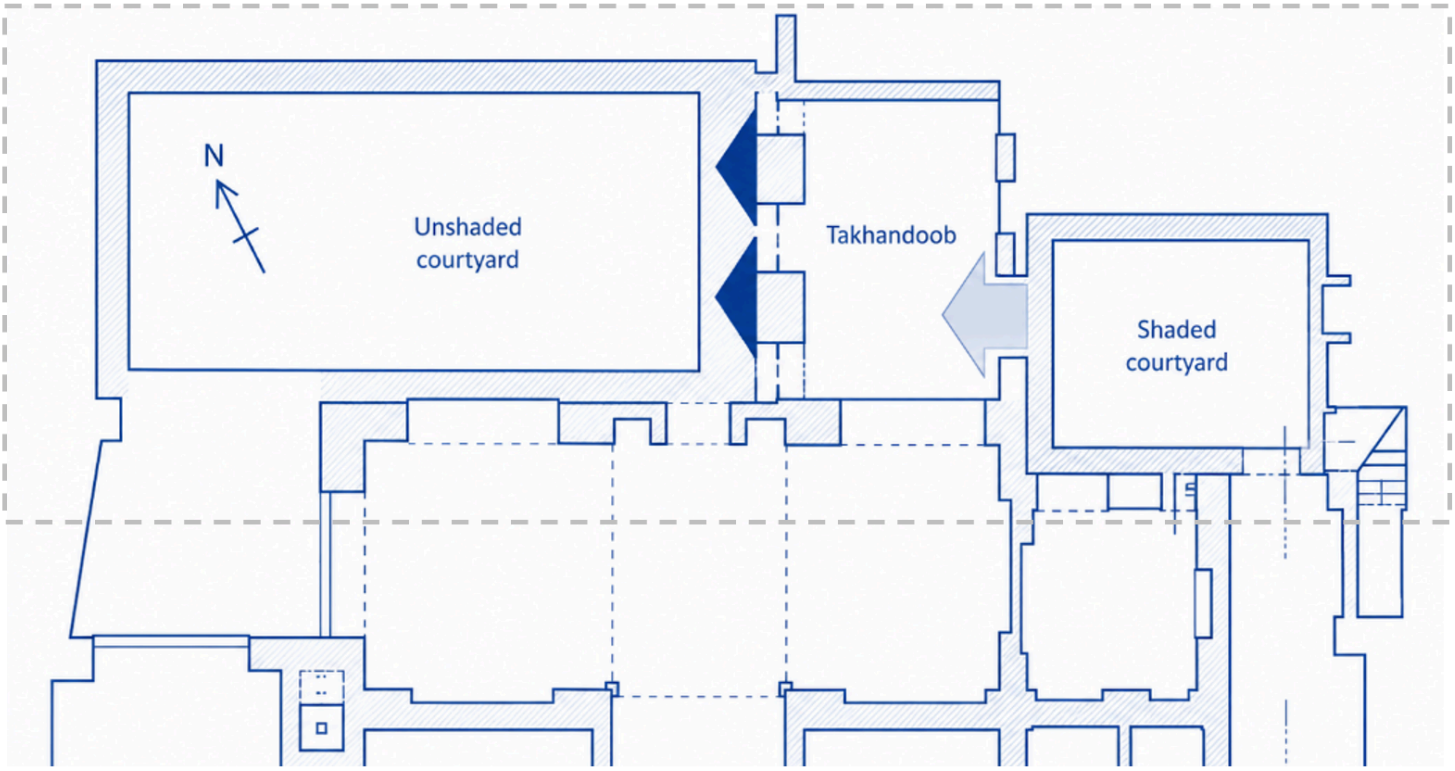


Figure 4

5. Plan of part of the ground floor of the Beit El Suhaymi, showing two courtyards with a Takhtabūsh between them.

Supplementary Files

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- Tables1to4.docx