Eurasian J. Sci. Eng., 2025, 11(2), 336-356
https://doi.org/10.23918/eajse.v11i2p24

Published by Tishk International University
Available at: https://eajse.tiu.edu.iq/

RESEARCH ARTICLE Open Access

Utilizing Natural Ventilation as a Passive Design Strategies to Enhance Energy Efficiency of Low-Income Houses in Erbil City.

Aya Hasan Ali [1]*, and Husein Ali Husein [1]

[1] Department of Architectural Engineering, Salahaddin University, Erbil, Kurdistan Region, Iraq.

Article History
Received: 14.08.2025
Revised: 10.09.2025
Accepted: 18.09.2025
Published: 28.09.2025
Communicated by: Prof. Dr. Bayan Salim
**Email address:*
aya.ali@su.edu.krd
**Corresponding-Author*

Abstract: Natural ventilation is a sustainable and cost-effective strategy for improving indoor environmental quality and reducing energy consumption, particularly in hot, arid climates. This study investigates the integration of natural ventilation strategies, specifically wind catchers, evaporative cooling, and façade openings, to enhance thermal conditions and energy efficiency in low-income housing in Erbil, Iraq. A mixed-methods approach was employed, including field surveys, IES-VE simulations, and statistical analysis using SPSS. Simulations were conducted under typical summer conditions as well as an extreme heat event, using local climate data and empirical wet-bulb temperature calculations to assess airflow and indoor temperature across varying building orientations, windcatcher geometry, and evaporative effectiveness levels (60%–90%). The results indicate that wetted wind catchers can reduce indoor temperatures by approximately 13.3 °C, with upper horizontal windows performing better than combined horizontal–vertical outlets. Statistical tests confirmed these effects as significant, reinforcing the potential of natural ventilation as a low-cost and sustainable cooling strategy. However, the study acknowledges certain limitations: simulations were restricted to summer and extreme heat conditions, excluding transitional and winter seasons, and evaporative performance was modeled at fixed efficiency levels, which may vary in real-world operation depending on water supply, quality, and maintenance. Overall, the findings demonstrate that combining traditional passive strategies with modern simulation tools offers a practical pathway to improving comfort and reducing energy demand in hot-climate, low-income housing.

Keywords: *Natural Ventilation; Windcatcher; Evaporative Cooling; Passive Design Strategies; Energy Efficiency; Low-Income Housing; Computational Fluid Dynamics (CFD)*

1. Introduction

The accelerating pace of global warming, climate change, and depletion of non-renewable energy resources constitute some of the most pressing challenges facing contemporary society. As [1] underscores, these environmental crises threaten not only the ecological equilibrium but also global socioeconomic and political stability. [2] further asserts that climate change may represent the most profound existential threat of the 21st century, primarily driven by human activities. The built environment plays a substantial role in this crisis. According to the United Nations Environment Program (2022), buildings account for 20–40% of global energy use and nearly 40% of CO_2 emissions. Without targeted mitigation, this figure is projected to rise by 50% by 2050 [3]. As [4] reports, residential buildings alone are responsible for approximately 21% of this consumption, particularly for heating, cooling, and ventilation needs.

The prevailing reliance on active mechanical systems such as air conditioning and mechanical ventilation has contributed significantly to energy demand and carbon emissions. Residential buildings in Erbil account for nearly 65% of the city's energy consumption. The city's semi-arid continental climate brings extremely hot, dry summers (June–September) with the hottest monthly averages around 43 °C and peak days exceeding 48 °C, and cold, wet winters [5]. Since 2003, rapid urbanization and population growth have accelerated housing construction, much of it delivered quickly with limited climatic consideration. As a result, many low-income dwellings suffer from weak envelopes and poor indoor environmental quality, driving reliance on energy-intensive mechanical cooling. Large paved areas around new estates intensify solar gains, while thin, uninsulated hollow-block walls and large single-glazed openings increase conductive and radiative heat transfer into living spaces. In the absence of purposeful passive design, residents resort to air-conditioning, locking in higher cooling demand. Without corrective measures, these issues will continue to burden future developments in high-insulation areas. Architects working in this context should therefore prioritize climate-responsive, low-energy strategies that improve comfort without escalating energy use [1]. Among the most effective and sustainable alternatives is natural ventilation (NV), a passive design strategy that utilizes wind pressure and thermal buoyancy to achieve indoor thermal comfort without mechanical systems. As [6] and [7] demonstrate, NV not only improves Indoor Environmental Quality (IEQ) but also significantly reduces operational energy costs, making it especially valuable in low-income housing contexts, where energy poverty and structural inefficiencies are prevalent

Recent reviews indicate that wind catchers can provide high air-change rates, improve indoor air quality (IAQ), and reduce overheating, especially when inlet size and shaft height are tuned and when low-energy add-ons (e.g., earth–air heat exchangers or evaporative cooling) are incorporated, with evidence from both hot-arid and temperate settings [8]. However, several limitations are relevant in Erbil: (i) climate dependence—direct and indirect evaporative cooling perform best in hot-dry conditions and lose effectiveness as outdoor humidity rises; (ii) water and maintenance—wetted media or brick liners require reliable water supply and regular cleaning, and dust loading reduces heat- and mass-transfer efficiency [9] [10]; (iii) aerodynamic trade-offs—increasing the cross-section raises volume flow but can shorten air–wall contact time and temper cooling gains, and low ambient winds reduce pressure differentials [11]; (iv) acoustics and air quality—aerodynamic noise and dust/pollutant ingress should be managed through geometry, baffling, and filtration [12]; and (v) modelling limits—many building-performance tools omit evaporative processes, so empirical wet-bulb (Tw) methods should be accompanied by sensitivity analysis and, where possible, validation [10]. Within the broader passive options, external shading/self-shading forms and thermal mass with night ventilation reliably suppress solar and diurnal loads, while double-skin façades and solar chimneys can add buoyancy-driven potential at higher cost and complexity; for Erbil's low-income stock (thin, uninsulated envelopes; single glazing; high solar exposure), the windcatcher-plus-evaporative pathway offers comparatively large, low-cost temperature reductions and fits local practice, with shading and thermal-mass measures recommended as complementary strategies [13]. This synthesis is consistent with the adaptive comfort approach in ASHRAE Standard 55 (2023).

The aim of this study is to investigate how natural ventilation can be optimized in low-income housing in Erbil to improve energy efficiency and indoor comfort. By combining traditional elements-wind catchers (badgirs), evaporative cooling, and façade openings (single-sided) with modern simulation tools and empirical equations, the research proposes a cost-effective strategy for cooling two-bedroom units.

In this research, the main hypothesis: Integrating natural ventilation strategies in low-income housing in Erbil City significantly reduces indoor temperatures and energy consumption during summer months.

The sub-hypothesis: H1. The implementation of wind catchers with evaporative cooling significantly reduces bedroom temperatures, H2. Window opening type and location significantly impact the indoor room temperature in low-income housing during summer.

The Main research question: Does integrating natural ventilation strategies in low-income housing in Erbil City significantly reduce indoor temperatures and energy consumption during summer months?

The sub-research questions are: Q1. Does the implementation of wind catchers with evaporative cooling significantly reduce bedroom temperatures in low-income housing during summer months? Q2. How does the type and location of window openings affect indoor room temperature in low-income housing during summer?

2. Literature review

Across hot, dry, and warm climates, a focused body of evidence shows that natural ventilation (NV) can substantially reduce cooling demand and improve comfort when geometry, opening control, and climate factors are explicitly tuned. In Khartoum (hot–dry), [14] coupled CFD with Integrated Environmental Solutions – Virtual Environment (IES-VE) software to test orientation, roof tilt, and window layout; combining cross-ventilation, night flushing, shading, and climate-appropriate openings delivered up to ≈71% annual cooling-energy savings with indoor air speeds concentrated in the comfort range—highlighting the primacy of dual-aspect openings and summer night ventilation. In Burkina Faso offices, [15] jointly optimized NV and daylight; an H-plan with selective glazing, horizontal louvers, and ~30% Window-to-Wall Ratio(WWR) cut annual energy by 14.9% and cooling by 25.3%, illustrating multi-objective tuning in warm climates. For schools, [16] found that façade-controlled NV in Japan could maintain ≈26 °C/60% RH in transition seasons and reduce energy by ~30%, though performance depended on occupancy schedules and internal gains.

Within the passive toolkit, wind catchers emerge as effective NV devices when height, cross-section, diffuser/roof form, and opening control are tuned to context. Systematic reviews [17]and[18] report robust *air changes per hour (ACH)/* Indoor Air Quality(IAQ) and overheating mitigation, with performance strengthened in hot–dry conditions by coupling to evaporative cooling (direct evaporative cooling DEC/indirect evaporative cooling IEC) or earth–air heat exchangers. In a temperate-city tested, Vienna, [19] showed that wind catcher height and aperture tuning, along with integration to earth tubes/heat pumps and Building Management System (BMS) set-points, can cut cooling loads and broaden seasonal utility—while urban morphology and obstructions remain decisive.

Evidence specific to low-income contexts is growing but still geographically sparse. In Erbil schools, [20] used IES-VE + MicroFlo to show that a four-sided windcatcher at ~6 m height balanced cost and performance: peak temperatures fell by 3–5 °C, comfort hours rose to ~65–75% (from <10%), and CO_2 compliance improved (often <1000 ppm), with night-flushing providing additional savings. Classic experimental work in Iraq [21] demonstrated that wetted brick wind catchers can lower indoor temperature by up to 12 °C with RH ≈29–35%, validating the evaporative augmentation pathway and noting the need for better air distribution in larger cross-sections.

Most prior work on natural ventilation (NV) examines individual and combined strategies such as wind-catchers, courtyards, or solar chimneys or reports comfort outcomes without systematically optimizing affordability and energy efficiency for low-income housing. Evidence integrating traditional wind-catchers (badgirs) with complementary passive measures, notably evaporative cooling and façade outlet design at the bedroom scale for two-bedroom units, remains limited, especially in hot-arid contexts comparable to Erbil. Few studies quantify the joint effects of wind-catcher geometry and orientation, evaporative effectiveness, and single-sided outlet configuration under realistic local climate constraints and cost limits. Consequently, there is insufficient, context-specific knowledge on how to design and operate NV systems that enhance energy efficiency in low-income housing while keeping construction and operational costs low—particularly for two-bedroom units in Erbil's hot-arid climate.

2.1 Wind Catchers as Passive Natural Ventilation Systems

Wind catchers, or badgirs, are traditional passive ventilation systems widely used in hot, arid regions of the Middle East and Eastern Asia to enhance indoor thermal comfort and air quality without mechanical energy consumption. These vertical shafts, ranging from 2 to 20 meters in height, utilize wind-driven and buoyancy-induced pressure differences to induce airflow into buildings. [22] Their performance is influenced by several geometric and contextual parameters, including height, cross-sectional shape, number and orientation of openings, internal partitions, and roof design [23][18]. External conditions—such as wind speed, direction, and surrounding structures—substantially impact windcatcher efficiency. For instance, the wind's direction and speed in relation to the wind-catcher have a significant impact on the induced airflow rate. [24]

2.2 Wind Catchers Integrated with Evaporative Cooling

The integration of wind catchers with evaporative cooling is a centuries-old strategy in Middle Eastern architecture to improve indoor thermal comfort in hot, arid climates. This hybrid system enhances ventilation by introducing ambient air through a water medium—such as ponds, spray systems, or wetted surfaces—thereby reducing air temperature and increasing humidity [25]. Studies by [26] using CFD and numerical models found that water-assisted wind catchers can lower indoor temperatures by up to 15 °C and raise relative humidity by 5%, with a cooling load potential of up to 100 kW. Evaporative cooling can be categorized into direct (DEC) and indirect (IEC) methods. In DEC, air directly contacts water, reducing temperature and increasing humidity; its effectiveness depends on the difference between dry and wet bulb temperatures [27]. IEC, in contrast, uses a heat exchanger to cool air indirectly, maintaining humidity levels in the supply air while improving thermal conditions.

2.3 Façade Openings and Natural Ventilation Performance

The position, number, and layout of façade openings are critical determinants of natural ventilation effectiveness in buildings, especially in hot climates [28]. External factors such as site vegetation and surrounding buildings can influence wind speed and pressure gradients, thereby altering air movement patterns [29]. Landscaping elements like trees and green façades reduce radiant heat and enhance airflow via evapotranspiration [30]. Building orientation and geometry also shape airflow patterns, with compact or U-shaped forms performing better in warm climates [31]. The size, location, and ratio of inlet-to-outlet openings directly impact airflow rates and recirculation zones. [32]

3. Methodology

This study employed a mixed-methods approach, integrating both qualitative and quantitative strategies to evaluate natural ventilation performance in low-income housing in Erbil City. As shown in Figure 1, the methodology was organized into four key phases. The qualitative phase began with the development of a theoretical framework, guided by a review of relevant literature. Natural ventilation strategies such as modified wind catchers, evaporative cooling, and single-sided façade openings were identified as independent variables, with energy efficiency defined as the dependent variable. A site survey of 27 residential compounds along Koya, Baharka, Pirmam, and Banslawa Roads was conducted, utilizing data from the Erbil Investment and Meteorological Authorities to document building layout, orientation, and income classifications. The quantitative phase involved simulation using (Integrated Environmental Solutions – Virtual Environment) IES-VE software [33] to assess airflow and indoor temperature under varying ventilation scenarios. The simulations were calibrated using local climate data reflecting Erbil's semi-arid continental climate, with peak summer temperatures exceeding 42 °C, winter lows reaching –5 °C, and average wind speeds ranging from 0.5 to 2 m/s. This integrated methodology enabled a robust assessment of both traditional and modified ventilation strategies, optimizing thermal comfort and energy efficiency under realistic conditions. As a final step, statistical analyses were conducted using Statistical Package for the Social Sciences (SPSS) software to test the main and sub-hypotheses. T-tests and correlation analyses were applied to validate the simulation results and quantify the significance of variables such as windcatcher orientation, window configuration, and evaporative cooling effectiveness.

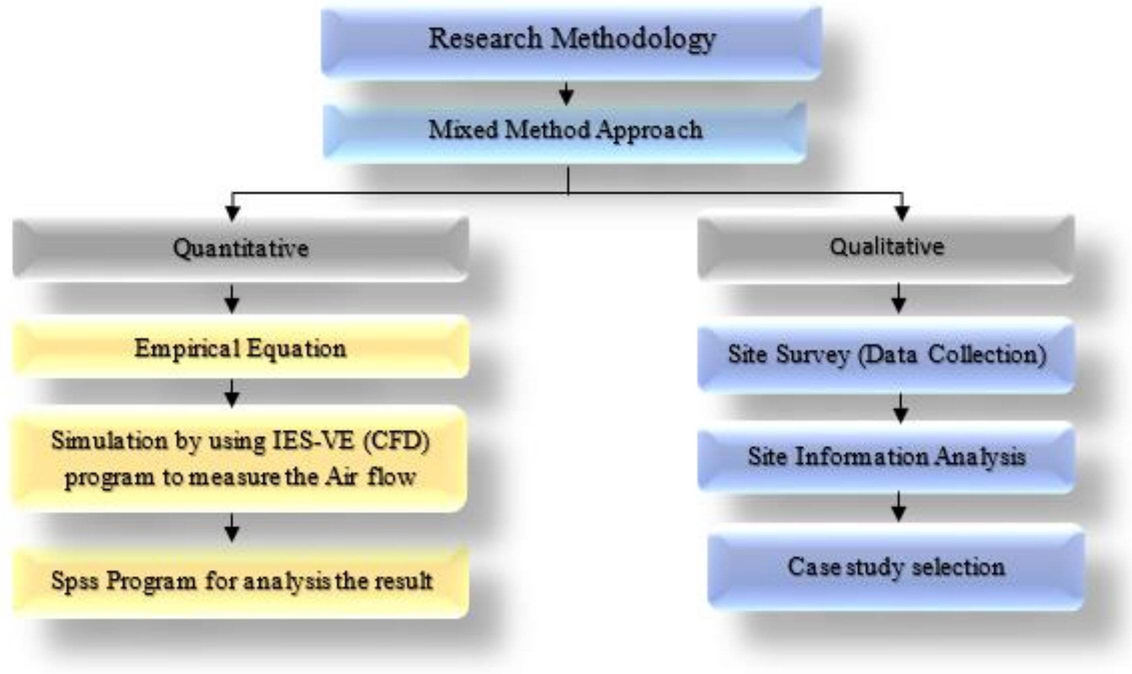


Figure 1: Research Methodologies

3.1 Case Study Selection and Description

Selecting a case study is an important step in ensuring that the research is relevant, valid, and applicable. In this study, certain criteria were devised to guide the selection process, with an emphasis on the site's appropriateness in meeting the research objectives. The requirements include:

- The compound was constructed for low-income families, which means the cost per square meter is below the city's average housing price and the use of cost-effective materials (e.g., concrete blocks, prefabricated elements, or, in some areas, mud brick)
- Small to medium-sized dwelling units (160-250m²) with efficient space utilization.
- Data Availability: Only compounds with complete architectural and site documentation were considered.
- Wind Catcher Integration Feasibility: Units needed to accommodate a single wind catcher capable of ventilating two bedrooms to optimize thermal performance with minimal modification. These criteria ensured the validity and feasibility of the subsequent simulation work

Accordingly, an extensive site survey was conducted, and data were obtained from the Erbil Investment Authority. Based on the first criterion, 27 low-income housing compounds were identified as low-income across four major sectors of Erbil City—Pirmam, Baharka, Banslawa, and Koya Roads—where land affordability has favored compact, single-story units. Typical plots range from

160–250 m², with built-up areas of 95–140 m². A classification system was then developed to map the compounds by typology, year of construction, plot dimensions, and architectural uniformity.

From the initial 27 compounds, 8 were excluded due to insufficient architectural documentation and 5 due to prefabricated construction or design incompatibility (e.g., Korea Village). The remaining candidates were subsequently assessed against a third criterion—the feasibility of integrating a single wind catcher serving two adjacent bedrooms with minimal modification (i.e., two bedrooms connected to one shaft) as seen in (Figures 2), which led to additional exclusions. Ultimately, 7 compounds met all selection criteria: Gulan City; Harsham 1, 2, and 3; Lawan City; Mamostayan City; and Altun City.

For simulation consistency, two windcatcher dimensions were adopted based on design compatibility and aerodynamic performance:

- 120 × 75 cm: Gulan City, Harsham 1–,2 and 3, Lawan City
- 140 × 75 cm: Altoun City, Mamostayan City

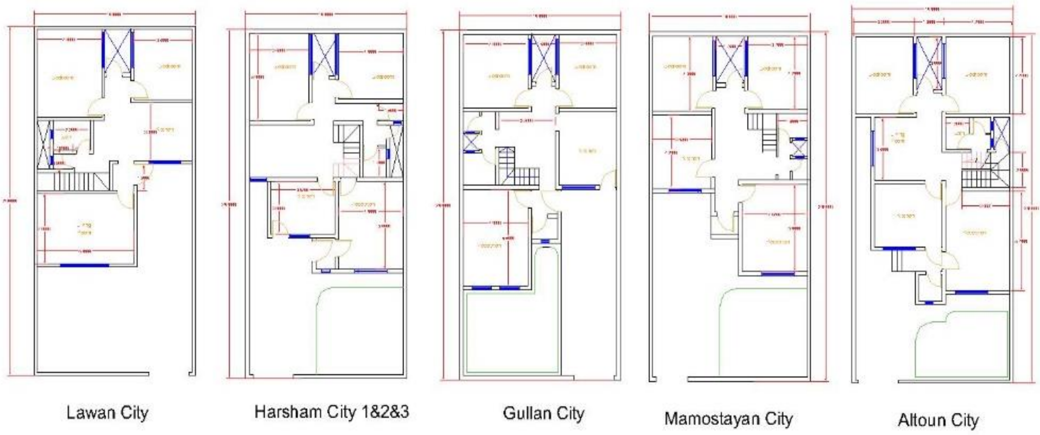


Figure 2: First Floor plan for Lawan City, Harsham1,2 and 3 City, Gullan City, Mamostayan City, and Altoun City (Researcher)

The selected case studies comprise low-income housing units with plot sizes between 166 m² and 250 m². Most units include two bedrooms, a kitchen, a living/reception area, and a bathroom, with some layouts incorporating an additional sitting room. The construction system is typically basic and cost-effective, using hollow concrete blocks for walls and aluminum-framed single-glazed windows. Roofs may include a thin Styrofoam insulation layer, though thermal insulation is otherwise minimal. For ventilation enhancement, Windcatcher Model No. 7 was chosen for simulation as Fig. 3 due to its proven effectiveness and acoustic acceptability, as documented in projects in Baghdad and Mosul since 1988. [21] While covered wind catchers, as shown in Fig. 4, offer better aerodynamic performance, they may produce disturbing aerodynamic noise at high wind speeds, particularly problematic in bedrooms. Thus, the selected model balances performance and user comfort as shown in Figure 4

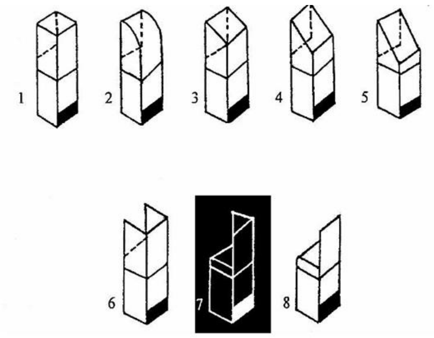
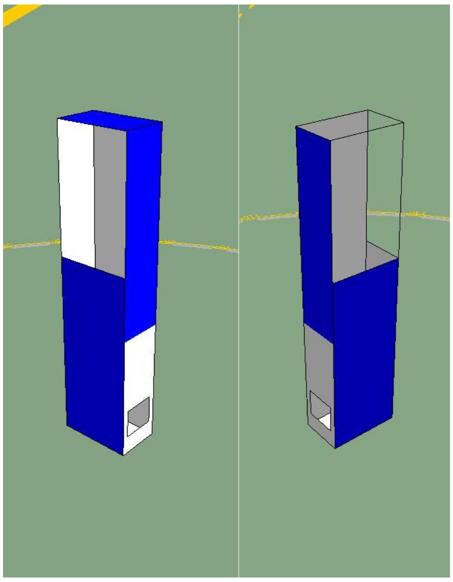


Figure 3: Different design models of windcatcher covers appropriate for building applications in Iraq [21]



(a) (b)

Figure 4: (a) covered wind catcher (b) Two sides opening wind catcher (Researcher)

Wind catcher walls were constructed using 20 cm-thick Thermostone blocks on the two exterior-facing sides and thermal insulation foam panels on the sides adjacent to interior spaces, offering both energy efficiency and cost reduction. Two wall heights, 4.5 meters and 7.5 meters, were employed to evaluate performance variation. Internally, wind catcher walls were plastered, waterproofed with three layers of cold bitumen up to 4.5 meters, and lined with high-porosity fired bricks (750°C–1150°C) to enhance capillary action and support evaporative cooling. Bricks with sealed pores or low porosity were excluded due to susceptibility to moisture damage. An automated spray system consisting of perforated 12 mm plastic pipes with 4 mm holes spaced every 10 cm was installed along the upper brick zone.

The system is connected to a 500-liter main water tank fed by a 2,000-liter auxiliary tank with a flow regulator. Excess water is managed by a pump installed in the basin of the wind catcher. A diffuser at the top ensures uniform air distribution, increasing contact with the wetted surfaces to maximize thermal exchange and cooling efficiency. [21].

This system design is illustrated in Figure 5, reflecting construction and operational details aligned with local Iraqi applications.

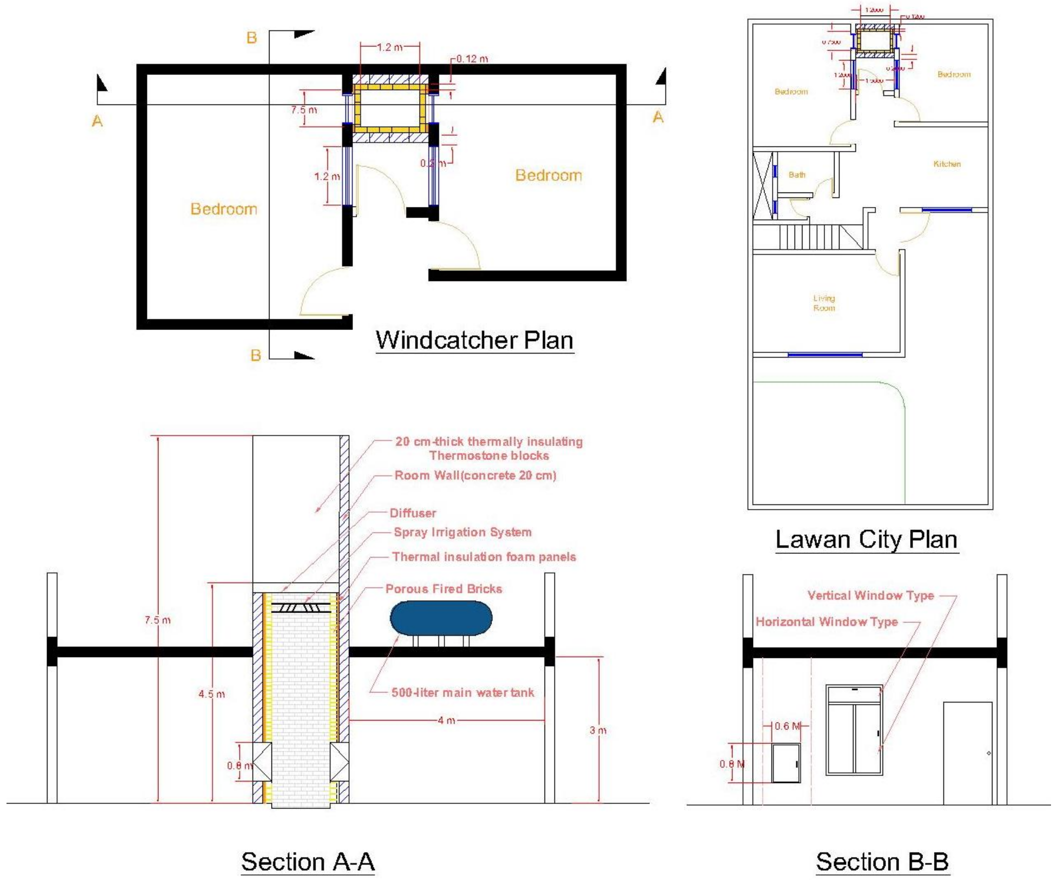


Figure 5: House Plan after adding the wind catcher, wind catcher plan, and sections (Researcher)

3.2 Methods for Evaluating the Performance of Natural Ventilation

Natural ventilation can be assessed through experimental or theoretical methods. Experimental approaches include full-scale field studies and wind tunnel testing. While in-situ studies provide high accuracy, they are often costly and less generalizable. Small-scale models offer better control and lower cost but face limitations in replicating real-world systems like wind catchers [23]. Theoretical methods involve analytical and numerical modeling. Analytical models provide quick estimates using fluid dynamics equations, but lack precision in complex scenarios. Computational Fluid Dynamics (CFD) is widely used for its ability to simulate detailed 3D airflow and thermal behavior, though its accuracy depends on high-quality input data and experimental validation [17], [34].

This study employed a theoretical approach, starting with analytical calculations to derive key parameters, followed by CFD simulations to evaluate and optimize natural ventilation strategies in low-income housing.

3.3 House Modelling for Simulation

Computational Fluid Dynamics (CFD) was employed to analyze airflow behavior within the windcatcher (badgir) using a plug-in available in the Integrated Environmental Solutions – Virtual Environment (IES-VE) software, which was also applied to construct and simulate the building models. IES-VE is a widely recognized building-performance platform for assessing thermal comfort and energy efficiency [33] [35]. To represent evaporative cooling, the model assumed that as outdoor air passes over wetted walls, evaporation absorbs latent heat, thereby reducing the dry-bulb temperature [10]. This cooling effect was quantified by calculating the wet-bulb temperature (Tw), a key indicator of evaporative cooling potential. Tw represents the lowest achievable air temperature through evaporation alone and is particularly significant in hot, arid climates, where the large difference between dry- and wet-bulb temperatures provides substantial cooling capacity. [36][27].

To estimate Tw, this study adopted the Stull formula [37], a widely accepted, non-iterative equation developed by Roland Stull, which calculates wet-bulb temperature based on dry-bulb temperature (Td) and relative humidity:

(1) Tw = T * atan[0.151977*(RH% + 8.313659)^(1/2)] + atan(T + RH%) - atan(RH% - 1.676331) + 0.00391838*(RH%)^(3/2) * atan(0.023101*RH%) - 4.686035

Where: Tw = wet-bulb temperature in °C T = dry-bulb temperature in°C, RH = relative humidity in This formula has been extensively applied in HVAC engineering and passive system analysis due to its balance of accuracy and computational efficiency [37] [38] [39] [40] [41]. It is particularly useful when psychometric tools are unavailable or when modeling needs to be incorporated into thermal simulation software. By estimating Tw using the Stull formula, researchers can approximate the air temperature drop resulting from evaporative cooling and input this value into IES-VE simulations, thereby enabling a realistic evaluation of indoor thermal conditions. Figure 5 illustrates the application of this approach within the simulation workflow.

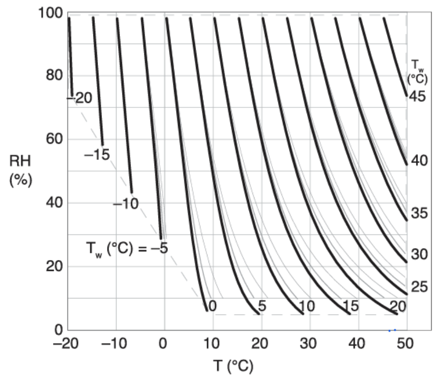


Figure 6: Isopleths of Tw [25].

4. Results

As outlined in the methodology, the Stull formula was used to estimate wet-bulb temperature (Tw) based on dry-bulb temperature (Td) and relative humidity (RH). Meteorological data from Erbil's Directorate indicate that during the summer months of June, July, and August in 2022–2024, the wind direction was either east or west, the average Td was 42.3 °C, with a corresponding RH of 32.2%, resulting in a Tw of approximately 28.31 °C. Average wind speed during the same period was recorded at 1.26 m/s at a reference height of 10 meters. To align with the model simulation height of 7.5 m, the Power Law Wind Profile [42] was applied, yielding an adjusted wind speed of approximately 1.15 m/s. The study evaluated three passive ventilation strategies: Wind catchers, Evaporative cooling (via wetted wind catcher walls), and Operable façade windows
The key variables investigated include:

- Cooling efficiency of the windcatcher system, which was analyzed across a range from 60% to 90%.
- Orientation of the windcatcher openings relative to prevailing wind directions and the overall building orientation. (East and West only)
- The impact of extreme outdoor temperature on indoor environmental conditions.

- Single-sided ventilation was modeled with outlet windows on the same façade as the windcatcher; outlet geometry was either horizontal or combined horizontal–vertical, at varying heights.

These parameters were incorporated into the IES-VE simulation framework to evaluate their combined effect on airflow patterns, indoor temperature reduction, and thermal comfort improvement in Erbil's low-income housing. The cooled air temperature resulting from indirect evaporative cooling was calculated using the following equation [43] [44] [45] [10]:

(2) $$T_{dry\ cool} = T_{dry\ out} - \varepsilon * (T_{dry\ out} - T_{wet\ in})$$

Where: $T_{dry\ out}$ = 42.3°C (ambient temperature) $T_{wet\ in}$ = 28.31°C (calculated using the Stull formula) ε = 0.60 - 0.90 (evaporative efficiency)
This equation estimates the cooled air temperature after passing through the wetted surfaces of the wind catcher. Table 1 shows a numerical example, and a summary table of results across different efficiency levels is provided to illustrate the effect of evaporative cooling under typical summer conditions in Erbil City.

This number indicates that the cooled air temperatures entering the bedrooms represent the result of the indirect evaporative cooling process occurring within the windcatcher, whose interior walls are wetted. As outdoor air flows through the window catchers, it exchanges heat with the cooler, moist surfaces, leading to a reduction in temperature before entering the indoor spaces.

The resulting supply air temperature varies depending on the degree of contact between the airflow and the wetted surfaces. In cases of limited air–wall interaction, the cooled air temperature may reach

Approximately 33.91°C, while greater surface contact can enhance cooling efficiency, reducing the air temperature to around 29.71°C. This range reflects the potential performance of the system under varying levels of evaporative efficiency, corresponding to values between 60% and 90%

Table 1: represents the result from the indirect evaporative cooling performance equation (Researcher)

evaporative effectiveness	$T_{Dry\ out}$ C°	$T_{Wet\ in}$ C°	$T_{Dry\ cool}$ C°
60%	42.3	28.31	33.91
70%			32.51
80%			31.11
90%			29.71

4.1 Analysis of Wind Catcher Performance Under Different Ventilation Scenarios

Four simulation scenarios were developed using IES-VE software to evaluate the effectiveness of natural ventilation through wind catchers and the bedrooms in the housing unit with a windcatcher of 120 × 75 cm (Lawan, Gulan, Harsham 1–3). The scenarios varied based on two factors: the shape of the window air-outlet (horizontal-only vs. combined horizontal and vertical strips) and the orientation of both the building (East or West) and the windcatcher openings (North-East vs. South-West). Climatic conditions were held constant across all simulations, with an outdoor temperature of 42.3 °C, relative humidity of 32.2%, wind speed adjusted to 1.15 m/s (at 7.5 m height), and a wet-bulb temperature of 28.31 °C calculated via the Stull formula. Evaporative cooling efficiency was assessed at four levels: 60%, 70%, 80%, and 90%. In Case 1 (East-oriented, combined window), wind catchers facing South-West yielded better cooling, reducing indoor temperatures to 27.70 °C at 90% efficiency, compared to 28.20 °C for North-East-facing openings as seen in Table 2 (Fig 7) shows that, at ε = 0.90, the combined outlet in an East-oriented block achieves 27.70–28.81 °C with SW openings, outperforming the NE configuration by ~0.5 °C. The temperature field indicates residual recirculation pockets near the vertical strips, consistent with higher outlet losses. Case 2 (East-oriented, horizontal-only window) showed the best overall performance, with temperatures dropping as low as 27.26 °C for South-West openings, indicating that simplified horizontal airflow can outperform more complex configurations when aligned with wind direction and building geometry as seen in Table 3 (Fig 8) shows replacing the combined outlet with a horizontal upper outlet reduces minimum bedroom temperature from 27.70 °C to 27.26 °C (SW). In Case 3, as shown in (Fig. 9) (West-oriented, combined window), North-East-facing wind catchers were more effective, achieving 27.64 °C at 90% efficiency, while South-West openings reached only 28.12 °C, suggesting a reversal in performance compared to East-facing cases due to changes in solar exposure and prevailing wind interaction. As seen in Table 2, finally, Case 4 Figure 10, together with Table 3, confirms that the horizontal upper outlet maintains its advantage under West exposure (down to 27.59 °C), while the orientation gap narrows as ε increases.

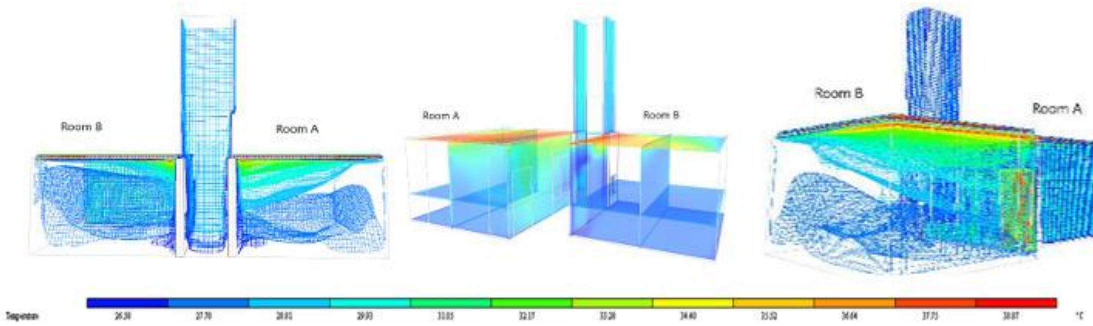


Figure 7: Case 1 House oriented to the East simulation for the bedrooms Temperature (~27.7-28.8) when the effectiveness of the evaporative cooling is 90 % (wind catcher opening facing South and West) (Researcher)

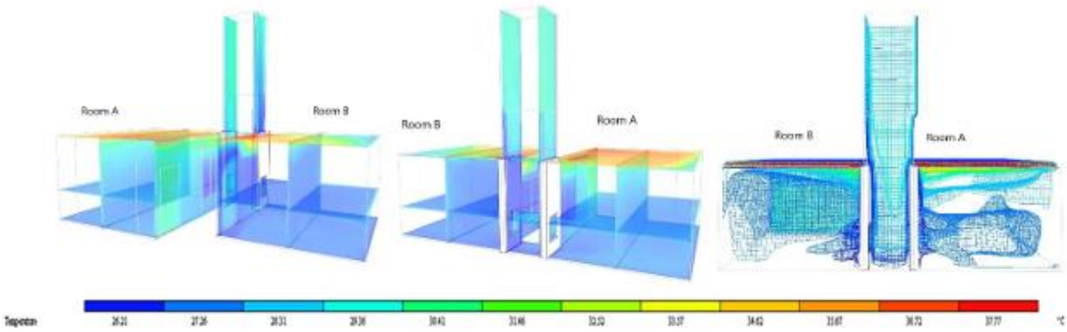


Figure 8: Case 2 House oriented to the East simulation for the bedrooms temperature (~27.26 C°) when the effectiveness of the evaporative cooling is 90 % (wind catcher opening facing South and West) (Researcher)

Table 2: for The Cases where the size of the wind catcher is (120 *75), Case 1& Case 3 (Researcher)

Case 1& 3 (single side HORIZONTAL AND VERTICAL windows opening) Lawan city , Harsham 1&2&3 Gulan city Houses Orientation EAST & West														
Air velocity M/S	wind Cather height(M)	Average of outdoor Temperature C°	Average of RH% for Outside	Wet bulb Temperature from STULL FORMULA C°	Evaporative Effectiveness	T Dry out(after passing on the wet wall of the wind catcher) C°	**Case 1 with EAST House Orientation**				**Case 3 With WEST House Orientation**			
							Windcatcher opening facing North and East		Windcatcher opening facing South and West		Windcatcher opening facing North and East		Windcatcher opening facing South and West	
							Room A Temperature C°	Room B Temperature C°	Room A Temperature C°	Room B Temperature C°	Room A Temperature	Room B Temperature	Room A Temperature	Room B Temperature
1.15	7.5	42.3	32.2	28.31	60 %	33.91	30.42 - 31.28	30.42	30.08 - 30.88	30.08	30.03	30.03	30.35-31.32	30.35-31.32
					70 %	32.51	30.01 - 30.83	30.01	29.57-30.57	29.57	29.55	29.55	29.87-30.85	29.87-30.85
					80 %	31.11	29.07 - 29.99	29.07	28.56 - 29.54	28.56	28.65-29.62	28.65	28.96-30.01	28.96
					90 %	29.71	28.20 - 29.18	28.2	27.70 - 28.81	27.7	27.64-28.51	27.64	28.12-29.05	28.12

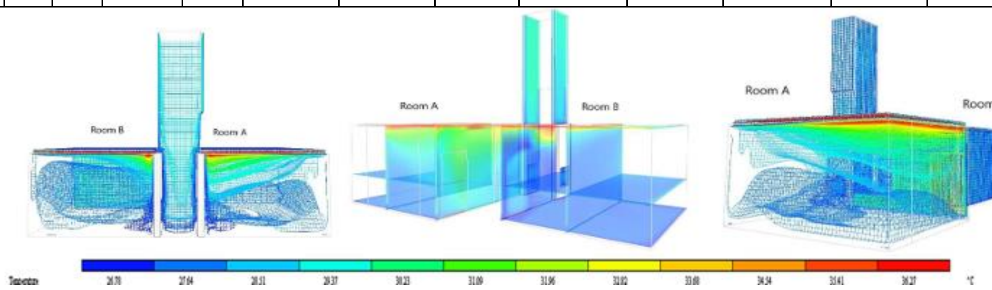


Figure 9: Case 3 House oriented to the West simulation for the bedrooms temperature (~ 27.6 C°) when the effectiveness of the evaporative cooling is 90 % (wind catcher opening facing North-East) (Researcher)

Table 3: for The Cases where the size of the wind catcher is (120 *75), Case 2& Case 4 (Researcher)

Case 2& 4 (single side HORIZONTAL ONLY window opening) Lawan city , Harsham 1&2&3 Gulan city Houses Orientation EAST & West														
Air velocity M/S	wind Cather height(M)	Average of outdoor Temperature C°	Average of RH% for Outside	Wet bulb Temperature from STULL FORMULA C°	Evaporative Effectiveness	T Dry out(after passing on the wet wall of the wind catcher) C°	**Case 2 with <u>EAST</u> House Orientation**				**Case 4 with <u>WEST</u> House Orientation**			
							Windcatcher opening facing North and East		Windcatcher opening facing South and West		Windcatcher opening facing North and East		Windcatcher opening facing South and West	
							Room A Temperature C°	Room B Temperature C°	Room A Temperature C°	Room B Temperature C°	Room A Temperature	Room B Temperature	Room A Temperature	Room B Temperature
1.15	7.5	42.3	32.2	28.31	60 %	33.91	28.35 - 29.36	30.36	28.54 - 29.65	29.65	28.05-29.10	30.15	28.35-29.35	30.35
					70 %	32.51	28.02 - 29.01	30	28.21 - 29.13	29.13	27.63-28.62	29.61	28.20-29.18	30.15
					80 %	31.11	27.84 - 28.80	28.8	28.05 - 29.93	28.05	27.55-28.50	28.50	28.13	29.06
					90 %	29.71	27.81	27.81	27.26	27.26 - 28.31	27.59-28.64	27.59	27.85	27.85

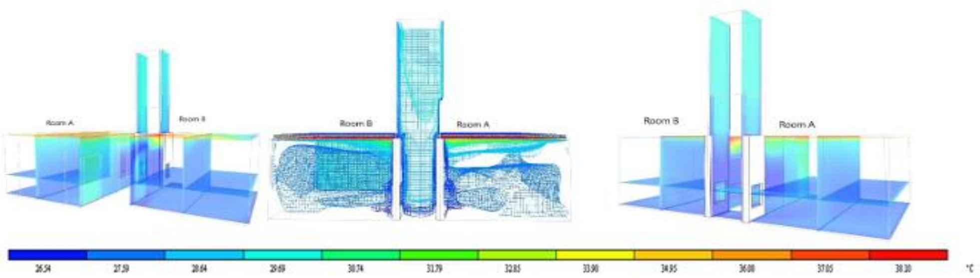


Figure 10: Case 4 House oriented to the West simulation for the bedrooms temperature (~27.59 C°) when the effectiveness of the evaporative cooling 90 % (wind catcher opening facing North-East) (Researcher)

4.2 Performance Analysis on Extreme Hot Day (11 August 2023)

To evaluate the resilience of natural ventilation strategies under extreme climatic conditions, two high-performing scenarios (Case 2 and Case 4) featuring horizontal-only window openings were simulated for 11 August 2023—the hottest recorded day in Erbil City over the past three years, with an outdoor temperature of 47°C and relative humidity of 30%. The wet-bulb temperature, calculated via the Stull formula, was 31.20°C. In Case 2 (East-oriented buildings), windcatcher openings were assessed facing either North-East or South-West. NE-facing wind catchers reduced indoor temperatures from 32.74°C at 60% efficiency to 30.26°C at 90% as seen in Fig 11, while SW-facing openings showed superior performance, reaching a minimum of 28.90°C at 90%, with enhanced cooling observed at higher evaporative efficiencies. The temperature reduction of up to 3.8°C compared to the ambient wet-bulb temperature highlights the system's potential during extreme heat events. In Case 4 (West-oriented buildings), both orientations demonstrated similarly effective cooling. NE-facing wind catchers reduced Room A’s temperature from 31.86°C to 28.55°C, whereas SW-facing openings achieved a slightly lower 28.50°C at 90% efficiency. The performance gap between orientations was minimal in this case, indicating that under extreme heat and low humidity, evaporative cooling dominates, diminishing the relative impact of orientation. Nonetheless, NE-facing wind catchers performed marginally better at moderate efficiencies (60%–70%), while SW orientations were more effective at higher levels (80%–90%), as summarized in Table 4.

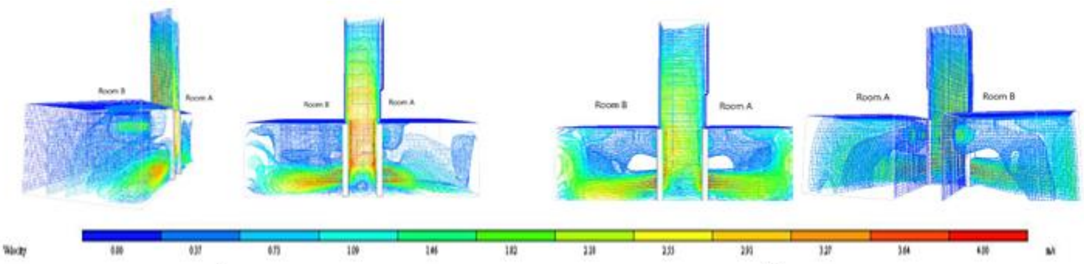
Table 4: for The Cases where the size of the wind catcher is (120 *75) Case 2& Case 4 the hottest day in the past three years (Researcher)

Case 2& 4 (single side HORIZENTAL ONLY window opening) Lawan city , Harsham (1-3) Gulan city Houses Orientation EAST & West 11August 2023 the Hottest Day in Past Three Years														
Air velocity M/S	wind Cacher height(M)	Average of outdoor Temperature C°	Average of RH% for Outside	Wet bulb Temperature from STULL FORMULA C°	Evaporative Effectiveness	T Dry out(after passing on the wet wall of the wind catcher) C°	**Case 2 with EAST House Orientation**				**Case 4 With WEST House Orientation**			
							Windcatcher opening facing North and East		Windcatcher opening facing South and West		Windcatcher opening facing North and East		Windcatcher opening facing South and West	
							Room A Temperature C°	Room B Temperature C°	Room A Temperature C°	Room B Temperature C°	Room A Temperature C°	Room B Temperature	Room A Temperature C°	Room B Temperature
1.27	7.5	47	30	31.20	60 %	37.52	32.74	32.74 - 33.67	31.94 - 32.86	31.94	31.86-32.97	31.86	32.87	32.87 - 33.93
					70 %	35.94	32.36	32.36	30.90 - 32.11	30.90	30.90-32.11	30.90	32.42	32.42 - 33.27
					80 %	34.36	31.30	31.30	29.87 - 30.85	29.87	29.92	29.92	31.25	31.25 - 32.15

					90 %	32.78	30.26	30.26	28.90 - 30.38	28.90	28.85-30.30	28.85	30.15	30.15 - 31.03

4.3 Comparative Evaluation of Wind Catcher Performance between City with Wind Catcher Dimensions 120*75 (Lawan Gulan and Harsham (1-3) Cities) and Cities with Wind Catcher Dimensions 140*75 Altoun City Mamostaian City

This comparative analysis investigates the performance of wind catchers in two low-income housing contexts (Lawan City) and Altoun City under hot-dry climate conditions, focusing on the effects of evaporative cooling, wind catcher geometry, orientation, and window design on indoor thermal comfort. The main geometric distinction lies in windcatcher dimensions: Lawan City employed wind catchers measuring 120 × 75 cm, while Altoun City used larger 140 × 75 cm units. As shown in Fig 11, the larger cross-sectional area in Altoun resulted in higher air volume, aligning with the Continuity Equation and Bernoulli's Principle, and supporting findings by [46], who noted that increased shaft area enhances airflow. Case comparisons further reveal consistent patterns: in Case 1 (East-facing, horizontal, and vertical windows), South-West-oriented wind catchers yielded optimal results, with Altoun reaching 27.67 °C and Lawan 27.7 °C at 90% evaporative efficiency, highlighting the advantage of aligning wind catchers with prevailing wind directions. In Case 2 (East-facing, horizontal-only windows), both cities achieved their lowest indoor temperatures: 27.26 °C in Lawan and 27.28 °C in Altoun, demonstrating that well-positioned horizontal openings near the roof can deliver highly efficient passive cooling when paired with favorable wind conditions. In Cases 3 and 4 (West-oriented buildings), Altoun simulations confirmed the superior performance of horizontal-only windows over combined openings, particularly at higher evaporative effectiveness levels. These results emphasize that orientation and airflow direction often outweigh window shape in determining ventilation success. Under extreme heat stress (47 °C on 11/8/2023), both cities demonstrated strong resilience. Lawan recorded indoor temperatures as low as 28.85 °C, representing a reduction of over 15 °C compared to ambient, aided by enhanced air velocity (1.27 m/s). Altoun City showed comparable performance, maintaining indoor temperatures between 30.06 °C and 30.9 °C, confirming that, under extreme conditions, wind catchers with evaporative enhancements will be highly effective in maintaining thermal comfort when optimally configured and oriented.



A B

Figure 12: (A) wind catcher with 120*75 simulation for Air velocity (wind catcher opening facing southwest) (B) wind catcher with 140*75 simulation for Air velocity (wind catcher opening facing southwest) (Researcher)

5. Discussion

The findings of this study confirm the main hypothesis that integrating natural ventilation strategies—specifically wind catchers with evaporative cooling—can significantly reduce indoor temperatures in low-income housing in Erbil. Across all scenarios, temperature reductions of approximately 13–15 °C were achieved, aligning with previous studies in hot-arid climates that demonstrated the effectiveness of modified wind catchers in enhancing thermal comfort and reducing cooling demand [21] [17]. These results indicate that such systems represent a practical and low-cost alternative to mechanical cooling, consistent with broader sustainability recommendations (UNEP, 2022) [6]

The statistical analysis using the Statistical Package for the Social Sciences (SPSS) further reinforces these conclusions. For Hypothesis 1, the one-sample t-tests confirmed a statistically significant reduction in indoor temperatures compared to the external reference of 42.3 °C ($p < 0.001$). On average, bedrooms recorded a temperature drop of approximately 13.3 °C, validating the effectiveness of wind catchers combined with evaporative cooling in substantially improving indoor thermal conditions. This finding aligns with [34] and [21], who demonstrated the benefits of integrating indirect evaporative cooling with windcatcher systems, reporting similar levels of cooling effectiveness. For Hypothesis 2, the independent-samples t-tests revealed statistically significant differences between window configurations ($p = 0.003$–0.010). The upper horizontal outlet windows consistently outperformed the combined vertical–horizontal outlets, particularly in east-oriented buildings, achieving up to 1.24 °C additional cooling. These results emphasize the critical role of window design in maximizing natural ventilation efficiency and enhancing passive cooling performance.

The superior performance of horizontal upper-side outlets can be explained by both aerodynamic and thermal principles. Aerodynamically, horizontal slots near the ceiling provide a smoother, less resistant flow path, reducing turbulence losses and maintaining higher air velocities [42]. Thermally, they align with buoyancy-driven stratification, efficiently exhausting the hot air that accumulates at ceiling level, while also benefiting from wind-driven suction effects. These combined mechanisms account for their superior performance compared to more complex outlet configurations.

Another significant finding relates to evaporative effectiveness. The Pearson correlation analysis revealed a strong negative correlation ($r = –0.719$, $p < 0.001$) between evaporative cooling effectiveness and the dry-bulb temperature of air exiting the wetted windcatcher. As the effectiveness increased from 60% to 90%, indoor air temperatures dropped from approximately 33.91 °C to 29.71 °C. This clearly demonstrates the strong cooling potential of the system under varying performance levels and highlights the sensitivity of indoor comfort conditions to evaporative efficiency.

Orientation effects also played an important role. South-West openings proved more effective in East-facing buildings, whereas North-East orientations performed better in West-facing cases. This reversal highlights the complex interaction of wind direction, solar exposure, and local microclimatic effects, consistent with findings from other arid-zone studies [3] (Mukhtar et al., 2019; Hafez et al., 2024). Furthermore, under extreme conditions (47 °C, 30% RH on 11 August 2023), the results support the principle noted by [10], who observed that evaporative cooling systems perform more effectively under low relative humidity, as drier air has a greater capacity to absorb moisture. This explains why the system remained highly effective even during extreme heat events.

Finally, the comparative simulations between Lawan City (120 × 75 cm windcatcher) and Altoun City (140 × 75 cm) demonstrated the influence of windcatcher cross-sectional area on cooling performance. The larger opening in Altoun primarily increased the volumetric airflow rate, as the greater cross-section was able to capture more wind, consistent with the Continuity Equation. However, according to Bernoulli's Principle, a larger area generally results in lower average air velocity for the same pressure differential, which in turn reduces the residence time of air in contact with the wetted walls. This limited the extent of evaporative heat exchange, and the resulting reduction in indoor temperature was relatively modest compared to expectations. These findings suggest that while larger wind catchers improve ventilation capacity, their cooling efficiency depends on achieving an optimal balance between airflow volume, air velocity, contact time, and the available evaporative surface area.

6. Conclusion

This research has provided a comprehensive and empirically grounded evaluation of natural ventilation as a passive design strategy, demonstrating its capacity to significantly enhance thermal comfort and energy efficiency in low-income housing within the hot-arid climate of Erbil. Through the integration of field surveys, advanced simulation using IES-VE/MicroFlo, and statistical validation via SPSS, the study achieved several important outcomes that directly address its stated objectives. Firstly, the results confirmed the main hypothesis, showing that the application of wetted wind catchers reduced indoor bedroom temperatures by approximately 13–15 °C compared to outdoor conditions, thereby establishing natural ventilation with evaporative augmentation as a viable and sustainable alternative to mechanical cooling. Secondly, the analysis quantified the relationship between evaporative cooling effectiveness and indoor temperature reduction, with the Pearson correlation ($r = -0.719$, $p < 0.001$) demonstrating that increasing effectiveness from 60% to 90% lowered cooled supply air temperatures from ≈33.91 °C to 29.71 °C, clearly highlighting the sensitivity of indoor conditions to system performance. Thirdly, the findings emphasized the role of window outlet configuration, where independent-samples t-tests ($p = 0.003$–0.010) established that upper horizontal outlets consistently outperformed combined horizontal–vertical openings by up to 1.24 °C, a result supported by aerodynamic reasoning—reduced turbulence and resistance—and thermal stratification principles that enable the efficient expulsion of warmer air from the ceiling zone. Fourthly, the study elucidated the impact of orientation, showing that South-West openings were more effective for east-oriented blocks and North-East openings for west-oriented blocks, while under extreme heat conditions (47 °C, RH = 30%) both orientations maintained resilience, achieving indoor temperatures as low as 28.5–28.9 °C, consistent with the principle that evaporative cooling performance improves in low-humidity conditions. Finally, the comparative analysis of different windcatcher geometries demonstrated that although larger cross-sections (140 × 75 cm) increased volumetric airflow in accordance with the Continuity Equation, the resulting cooling gains were modest, likely due to reduced air–surface contact time, thus underscoring the necessity of balancing airflow volume, velocity, and evaporative contact for optimal performance.

In light of these findings, the study recommends integrating wetted wind catchers with evaporative cooling into both new and existing low-income housing to lessen reliance on mechanical cooling. Optimizing windcatcher dimensions, prioritizing horizontal window outlets, and adopting cost-effective construction methods (e.g., hollow concrete blocks with brick linings for wetted surfaces) can make the strategy both technically feasible and socially acceptable, particularly given the cultural familiarity of wind catchers in Iraq. At the policy level, economic incentives, regulatory updates, and incorporation into housing standards would further support widespread adoption.

The study acknowledges certain limitations: simulations were restricted to summer and extreme heat conditions, evaporative performance was modeled at fixed efficiency levels (60–90%), and real-world variables such as water supply, quality, and maintenance were not accounted for.

Future work should expand the analysis seasonally to include spring, autumn, and winter ventilation penalties; assess neighborhood-scale influences such as urban morphology, building spacing, and vegetation; and explore hybrid approaches that combine NV with photovoltaic-assisted fans, low-cost shading, or phase-change materials for added resilience during heat waves. Field validation through pilot retrofits across multiple compounds, with on-site monitoring of thermal, humidity, airflow, and water-use performance, is also essential to calibrate effectiveness and refine long-term operation and maintenance strategies. Collectively, these findings demonstrate that natural ventilation, when carefully optimized, represents a robust, affordable, and socially acceptable pathway to reducing cooling energy demand in Erbil's low-income housing. By addressing remaining gaps through neighborhood-scale analysis, hybrid strategies, and real-world monitoring, NV can evolve from a promising passive design measure into a practical, policy-driven solution for sustainable housing in hot-arid regions.

Author's Contribution

We confirm that all named authors have read and approved the manuscript. We also confirm that each author has contributed according to their role in the research and writing of the paper. We further confirm that all authors have approved the order of authors listed in the manuscript.

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