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# Windcatchers in Modern Housing: Enhancing Air Quality and Thermal Comfort

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## Abstract

In light of the growing challenges posed by high energy consumption in the building sector and the urgent need for environmentally compatible solutions, revisiting and reapplying traditional architectural elements—such as the windcatcher—in contemporary building design has gained renewed importance. As one of the most effective natural ventilation systems in Iran's vernacular architecture, the windcatcher plays a significant role in providing airflow, reducing indoor temperatures, and enhancing thermal comfort in hot and arid regions. This study aims to investigate the modern applications of windcatchers in residential buildings by conducting both qualitative and quantitative analyses of their impact on Indoor Air Quality (IAQ), temperature and humidity control, and reduced dependency on mechanical ventilation and cooling systems. The research methodology combines a literature review with the analysis of contemporary case studies.

Findings indicate that proper design and strategic placement of windcatchers can significantly improve indoor ventilation, reduce indoor air pollution, and elevate thermal comfort levels. Furthermore, integrating windcatchers with local materials and modern technologies—such as non-mechanical evaporative systems—enhances energy efficiency and significantly lowers the building's cooling load.

Ultimately, this research demonstrates that the intelligent integration of traditional architectural principles with sustainable design criteria and modern scientific knowledge can offer practical solutions to address the energy crisis and climate change challenges faced by today's architects and designers.

**Keywords:** Windcatcher, Sustainable architecture, Climate, Natural ventilation.

## 1 | Introduction

In recent decades, the rapid increase in energy consumption in buildings—particularly for air conditioning and cooling—has become one of the significant challenges for urban societies in the context of sustainable development and combating climate change. The rise in global temperatures, the depletion of fossil fuel

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resources, and their environmental consequences have intensified the need to reconsider architectural design approaches and to adopt low-energy, ecologically-based solutions. Among these, natural ventilation strategies have gained a prominent position as one of the most effective methods for reducing building energy loads and improving Indoor Air Quality (IAQ).

The windcatcher, a prominent element of traditional Iranian architecture in hot and arid climates, is a prime example of a natural ventilation system that, for centuries, provided cooling, airflow, and thermal comfort in residential spaces without relying on fossil fuels. Despite its high effectiveness in meeting the climatic needs of inhabitants, the windcatcher has mainly been neglected in modern and contemporary architecture. In recent years, however, the growing interest in sustainable architecture and the revival of indigenous knowledge has renewed attention to windcatchers among designers and researchers. Still, the effective integration of this traditional element into modern building forms—especially in densely populated urban settings—remains ambiguous and challenging. Furthermore, most previous studies have focused on the historical or structural analysis of windcatchers, with limited attention given to their practical and adaptive use in contemporary architecture and their direct impact on IAQ and thermal comfort. The analysis of windcatchers has created a significant gap in the existing literature, particularly due to the lack of field studies and quantitative simulations in this area.

Accordingly, this study aims to propose design solutions based on the integration of traditional elements with the needs of contemporary architecture. The research seeks to answer the following key questions:

I. Can the windcatcher perform effectively in improving IAQ within the framework of modern architecture?

II. To what extent can the use of windcatchers enhance the thermal comfort of residents?

III. What impact does incorporating windcatchers into contemporary buildings have on reducing cooling energy loads?

To address these questions, the present study employs a mixed-method approach, including literature reviews and analysis of case studies. The findings suggest that the use of various types of windcatchers in hot and arid regions can increase indoor air velocity and reduce building energy consumption. The results further demonstrate that, with proper design and strategic placement, windcatchers can function as effective natural ventilation systems, lowering indoor temperatures, increasing natural air exchange rates, and reducing cooling energy demand. Ultimately, this research seeks to bridge the gap between traditional windcatcher concepts and their practical applications in contemporary architecture, aiming to present a localized and efficient model for residential building design in hot and arid climates.

# 2 | Research Background

The badgir (windcatcher) is one of the distinctive elements of traditional architecture in the hot and arid regions of Iran, such as Yazd, Kerman, and Kashan. It is designed for natural ventilation, temperature reduction, and thermal comfort. Windcatchers have a long history, dating back at least three thousand years. Ancient Iranians and early Assyrians first used them. For centuries, windcatchers have been employed in hot and dry regions such as Iran (known as badgir), Iraq, Afghanistan, Pakistan (known as baakhor), and Egypt (known as malqaf) for natural ventilation and evaporative cooling of interior spaces (*Figs. 1-5*) [1].

A windcatcher is a structure that extends above the roof of a building and consists of openings, roofs, channels, and internal partitions, with internal ducts connected to the living spaces. Windcatchers rely on two driving forces: wind and buoyancy. By harnessing wind forces and the stack effect (buoyancy), windcatchers provide energy-free ventilation [2]. At higher wind speeds, wind forces dominate, while in calm conditions, buoyancy forces prevail. Air flows in the direction of lower pressure, accelerating air movement within the room, enabling air exchange, and reducing the indoor temperature [3].

Typically, the windcatcher's openings face the prevailing local wind direction (*Fig. 6*) [2]. The windcatcher's openings create a positive pressure zone on the windward side, drawing fresh air into the building through narrow ducts. Stale air is then expelled through outlets on the negative pressure side of the building, facilitating air circulation.

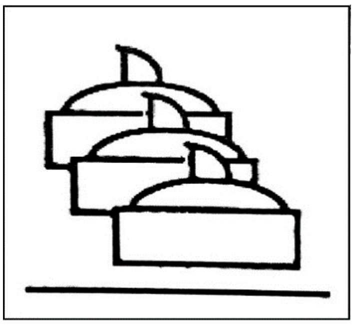


**Fig. 1. The initial concept of using tents and wooden structures to direct the wind inward.**

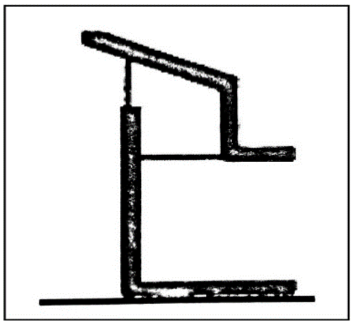


**Fig. 2. Cross-section of windcatchers in Egypt.**

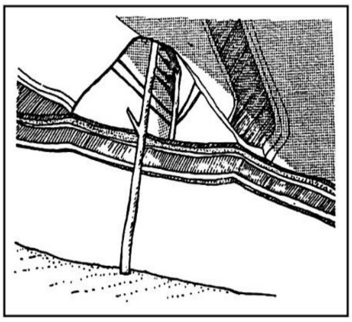


**Fig. 3. Windcatchers in Afghanistan.**

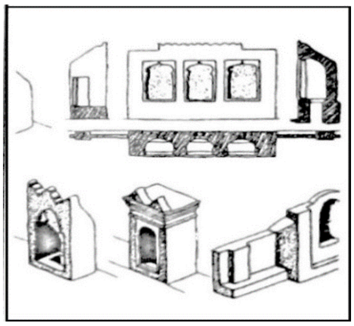


**Fig. 4. Cross-section of baakhor windcatchers in Pakistan.**

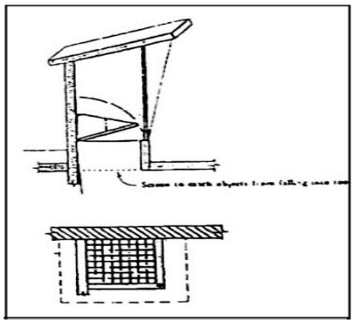


**Fig. 5. Various types of windcatcher examples in Iraq.**

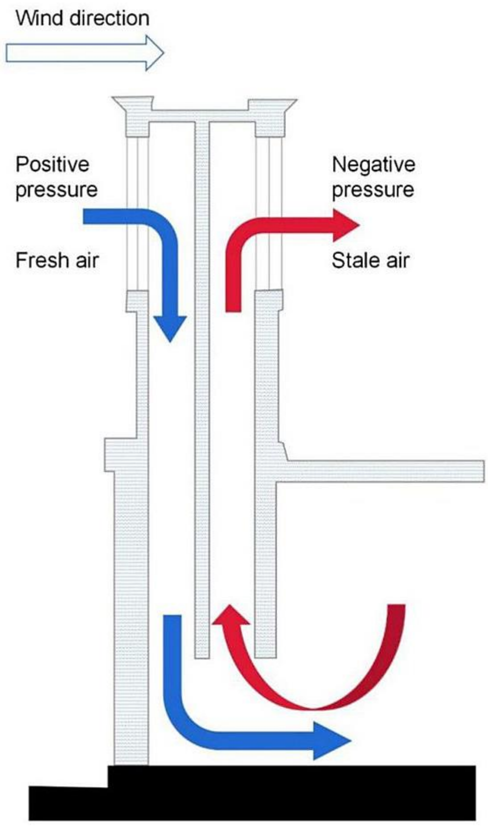



**Fig. 6. Part of the windcatcher's operating mechanism.**

*Fig. 6* shows part of how windcatchers work. In 1985, Bahadori [4], [5] conducted the first study on windcatchers and introduced two new designs: the 'windcatcher with wet surfaces' and the 'windcatcher with wet columns' (*Fig. 7*), which are distinct from traditional windcatcher designs. These new designs include structural improvements that enhance performance compared to traditional windcatchers. Bahadori carried out numerical analysis and experimental research on these designs and demonstrated their superior performance. Moreover, in areas with low wind speeds, the 'windcatcher with wet surfaces' performs more effectively than the 'windcatcher with wet columns'.

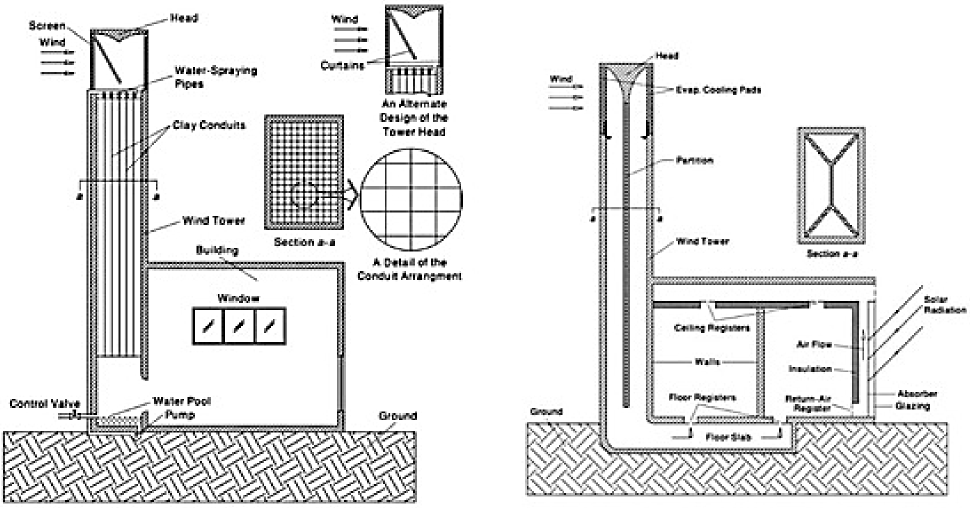



**Fig.7. Cross-sectional view of a windcatcher with wetted columns (left) and wetted surfaces (right) [5].**

# 3|Analysis and Discussion

The use of windcatchers in modern architecture has gradually faded from public view with the advancement of architectural design and the growing demand for thermal comfort. They are rarely seen in newly constructed buildings and appear primarily in renovated buildings—for example, an apartment in Greece built in the 1970s (*Fig. 8*). These buildings are located in urban areas where the low street width-to-building height ratio (approximately 0.6) results in reduced horizontal airflow (low wind pressure on facades), making natural ventilation through openings unlikely. However, strong rooftop winds prevail, allowing windcatchers to function efficiently.

Montazeri [6] and Montazeri et al. [7] and Hughes et al. [8] conducted experimental evaluations on the performance of windcatchers with different opening orientations, such as one-sided, two-sided, four-sided, and octagonal types (*Fig. 9*). The cross-sectional shape is one of the features distinguishing different types of windcatchers—such as rectangular, hexagonal, and octagonal—and is a topic many researchers are keen to study [9], [11]. To enhance the natural ventilation capabilities of windcatchers, researchers have investigated evaporative cooling and increasing heat sources [12], [16].

Most previous studies evaluating windcatcher performance have been based on the above classification criteria and have compared them within their respective vertical domains, without comparing windcatcher efficiency across different classification domains. As a result, they have been unable to provide accurate and comprehensive design recommendations for windcatchers. Therefore, this paper compares and evaluates various types of windcatchers from three perspectives: IAQ, thermal comfort, and offers suggestions for the design and development of future windcatchers.

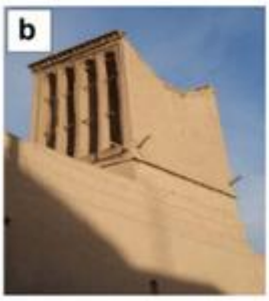

**Fig. 8. South elevation of the case study building showing the three wind-catchers integrated at the building core on top of the light wells [12].**

## 3.1 | Indoor Air Quality

The natural ventilation technology of windcatchers is a highly effective approach for enhancing air circulation, saving building energy, and improving IAQ and thermal comfort. To facilitate a comprehensive understanding of the performance of windcatcher-based natural ventilation in improving IAQ and thermal comfort, it is essential to classify and summarize the various types of windcatchers and clarify the methods and principles associated with each type.

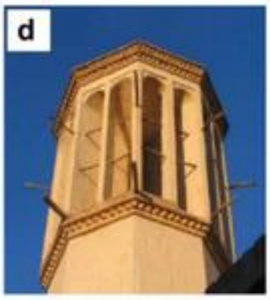
Windcatchers can be categorized based on the orientation of their openings, such as one-sided, two-sided, four-sided, and eight-sided designs (*Fig. 9*). Based on cross-sectional shape, they can be divided into square, rectangular, hexagonal, and octagonal types. Additionally, windcatchers can be classified according to their driving forces, including wind and buoyancy, heat sources, evaporative cooling, and hybrid systems.


a.




b.


c.




d.

**Fig. 9. Traditional windcatchers with different numbers of openings; a. one-sided, b. two-sided, c. four-sided, d. octahedral [14].**

**Wind and Buoyancy Forces**

The reliance of windcatchers on wind force or buoyancy force to achieve natural ventilation has been a topic of discussion in the research domain. Many studies on windcatchers have primarily assumed that airflow is driven by pressure differences (wind force), often neglecting the role of buoyancy [8]. However, conducted CFD modeling to investigate and compare these two forces. The study showed that wind, as an external driver, is the primary force behind windcatcher performance, resulting in 76% greater indoor ventilation compared to the secondary driver (buoyancy force).

Furthermore, in the absence of external airflow channels other than the windcatcher itself, the impact of buoyancy was negligible. Adding an external airflow channel, such as a window (*Fig. 10*), in combination with buoyancy, can increase indoor ventilation by up to 47%. However, this is not a standardized value and varies depending on location and climatic zone.

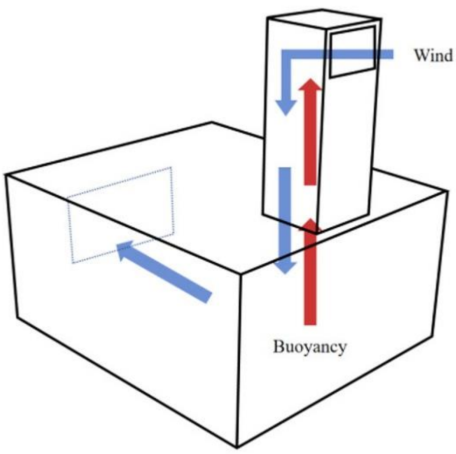



**Fig. 10. A windcatcher with an external airflow channel.**

## Heat Source

To address the issue of stagnant air, which often occurs during the operation of windcatchers, researchers commonly employ the strategy of installing a heat source inside the windcatcher. This method accelerates indoor airflow by heating the air and utilizing the buoyancy effect. Elmualim [12] investigated the impact of heat sources on the natural ventilation performance of windcatchers through smoke visualization experiments and CFD simulations. The findings showed that introducing a heat source into the test chamber increased the wind flow rate, especially at low wind speeds, when the maximum indoor temperature ranged from 30 to 32 °C and the outdoor temperature from 20 to 22 °C. The increase in airflow velocity was 54% and 7% at wind speeds of 1 m/s and 3 m/s, respectively.

An alternative approach uses solar radiation to heat the air, thereby enhancing air circulation. This technology, known as solar chimneys (*Fig.11*), consists of a black tube made of a material with high thermal conductivity. Solar energy heats the chimney wall, which in turn transfers heat to the air inside the tube. The heated air then exits through the top of the tube.

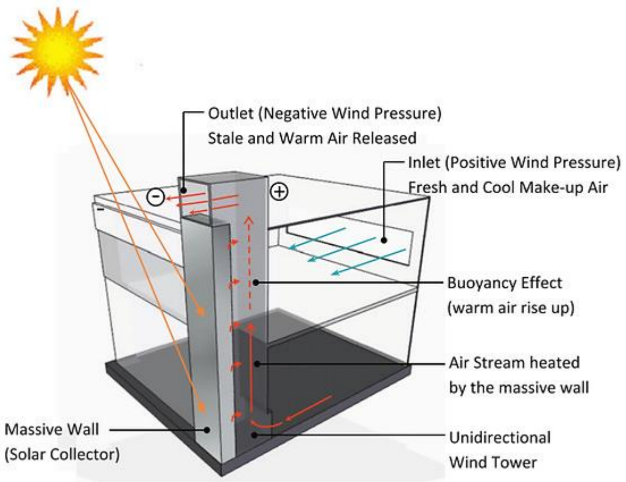



**Fig. 11. A solar windcatcher system integrated into a naturally ventilated building [14].**

## Evaporative and Hybrid Cooling

In general, the height of a windcatcher significantly affects its ventilation performance. Ideally, a taller windcatcher results in faster wind speeds, greater airflow, and higher natural ventilation efficiency. Additionally, higher elevations are usually correlated with cleaner air quality. However, this is not always the case. Some studies have shown that as windcatcher height increases, wind speed slightly decreases [17].

Ghadiri et al. [18] used CFD simulations in Yazd, Iran, and found that windcatcher height has a significant impact on thermal performance, with a 6-meter-high windcatcher showing the most important potential. This finding contrasts with traditional designs that may reach heights of up to 15 meters.

Moreover, the cross-sectional shape of a windcatcher is a critical factor affecting its natural ventilation performance. Several researchers have examined how the cross-sectional shape influences windcatcher efficiency. Pakari and Ghani [19] used full-scale wind tunnel testing and CFD simulations to assess the performance of square and circular windcatchers. The wind tunnel tests were conducted under various wind speeds and directions. The results showed that the normalized air supply volume of the square windcatcher, based on the inlet area, was significantly higher than that of the circular one.

Another detailed experiment investigated how different inlet geometries could enhance the natural ventilation efficiency of air traps (as shown in *Fig. 12*). The researchers tested four scenarios:

I. "Empty" geometry (*Fig. 12a*).

II. "Circular" (*Fig. 12b*).

III. "Parabolic" (*Fig. 12c*).

IV. Parabolic with a "Hyperbolic" bell mouth in the tower (*Fig. 12d*).

After comparing and analyzing the "empty," "circular," and "parabolic" shapes under various wind directions, it was found that the average Air Changes per Hour (ACH) was approximately 7.50 $h^{-1}$. However, the "hyperbolic" shape, due to the reduced cross-sectional area of the tower, showed a lower ventilation rate with an average ACH of 6.45 $h^{-1}$, performing worse than the other three shapes.

Following the addition of a windcatcher, further tests were conducted on the "empty" and "parabolic" configurations:

I. "Empty" + 1-meter windcatcher: Under oblique wind direction, ACH increased from 6.50 $h^{-1}$ to 7.70 $h^{-1}$.

II. "Parabolic" + 1-meter windcatcher: Similar to the empty configuration, performance improved under oblique wind but declined under longitudinal wind.

Finally, by refining the baffle design, performance improvements were achieved in all wind directions, resulting in an approximate 11.5% increase in average ACH [20].

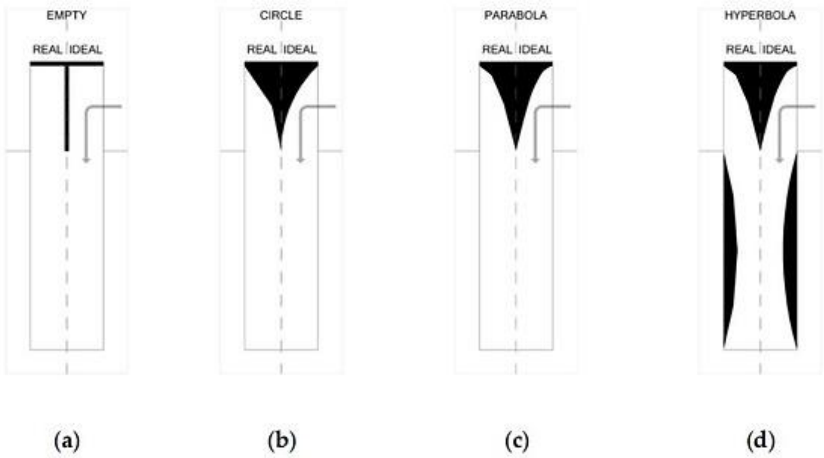



**Fig. 12. Conception of the wind catcher inlet structure shape; a. "empty" geometry, b. "circle", c. "parabola", d. parabola with a "hyperbola" bell in the tower [20].**

Hosseini et al. [21] used data from the Center for the Built Environment and thermal comfort tools to evaluate the design and performance of windcatchers based on thermal comfort metrics. In the simulation shown in *Fig. 13*, windcatchers with different inlet and tower geometries are presented. The height and width of the windcatchers were adjusted to determine optimal values.

The study revealed that changing the width of the windcatcher had the most significant impact on the velocity and distribution of airflow inside the room. Reducing the width from 2.5 meters to 2 meters increased the airflow speed in the central area of the room by 34%. A further reduction in width from 2 meters to 1.5 meters completely altered the airflow pattern inside the room and increased the airflow speed in the central area by 50%.

Ultimately, using the tools provided in this study, windcatchers can be optimized to improve comfort across different climatic conditions.

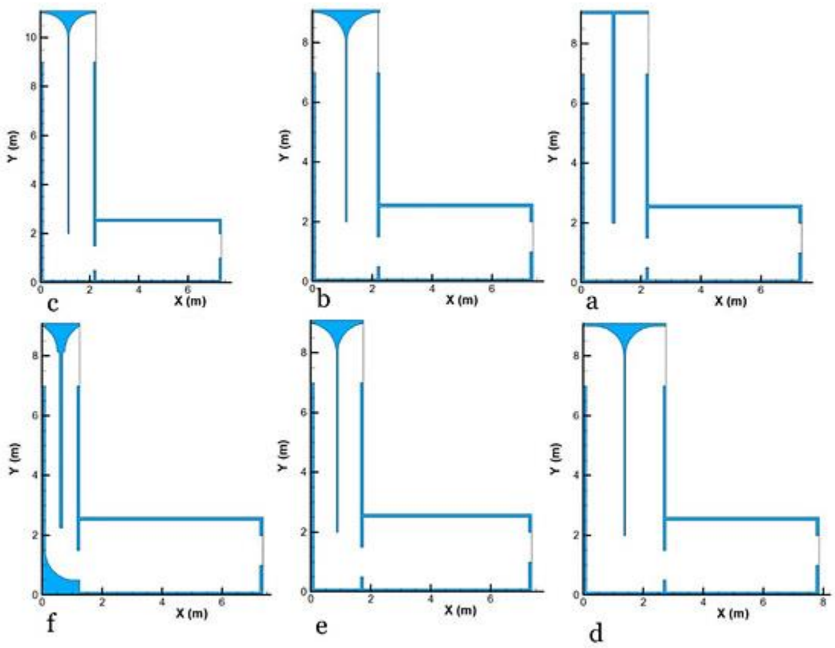


**Fig. 13. Windcatchers with different inlet and tower geometries [21].**

## 3.2 | Thermal Comfort Assessment

Thermal comfort is an index that measures the comfort level of the human body and is commonly used in the design and improvement of indoor environments. This concept was first introduced in the 1970s, when a set of standards was developed to help designers and indoor environment managers evaluate and enhance thermal comfort. The index takes into account multiple factors, including temperature, humidity, air velocity, and radiation, providing a more comprehensive method for assessing indoor environments [22].

The Chartered Institution of Building Services Engineers (CIBSE) defines thermal comfort as a high level of occupant satisfaction with the thermal environment [23]. Some studies have attempted to use heating units as heat sources to regulate the temperature of incoming air and maintain it within the comfort range (around 23°C). Experimental results have shown that an internal temperature change of 2 to 4°C can ensure adequate thermal comfort [24].

Nadia Saif and colleagues tested the effectiveness of combining wind catchers and solar chimneys for room cooling in the semi-arid climate of Algeria. Using a small-scale model room (80×80×100 cm) and a wind catcher of dimensions 15×90×200 cm, the solar chimney utilized solar radiation to heat the air, enhancing natural convection and contributing to indoor temperature reduction. Additionally, an evaporative cooling system cooled the air before it entered the room. The results indicated that during the test phase, indoor temperature dropped by 3 to 7°C, and the maximum air velocity reached 1.8 m/s. The combination increased the comfort period from 74% to 100%. Although IAQ improved, $CO_2$ concentrations exceeded the ASHRAE-defined limits during most occupancy periods [25].

Morales et al. [26] assessed the thermal comfort performance of wind catchers integrated with heating and humidification systems during both summer and winter, to determine the impact of air humidification under varying climatic conditions defined by temperature and relative humidity. The study revealed that air humidification improved wind catcher thermal performance by 124.2% in winter and 135.8% in summer compared to dry airflow. Spraying water into the air for humidification could lower the indoor temperature by up to 3°C. Humidification of incoming air had a significantly greater cooling effect in summer than in winter. Therefore, it is recommended that buildings using wind catchers incorporate air humidification technology in summer. To further enhance wind catcher efficiency during hot periods, the mass flow rate of water droplets should be increased to reduce high ambient air temperatures.

Abdo et al. [27] examined the performance of wind catchers using Phase Change Materials (PCM) as a passive cooling technology. They monitored and analyzed the system in terms of humidity, temperature, and air velocity. Experimental results showed that the average humidity levels in the PCM-containing cavities changed very little, with differences ranging from 0% to 3.88%. However, excessively high relative humidity could cause condensation and mold, indicating a need for dehumidification technologies to address this issue.

Overall, wind catchers have varying levels of effectiveness in enhancing thermal comfort in naturally ventilated rooms across different climatic zones. Varela-Boydo et al. [28] explored natural ventilation as an energy-saving strategy during building retrofits. Results showed that without mechanical cooling systems, natural ventilation strategies can increase ventilation rates up to 7 times and reduce indoor air temperature by 2°C. The cooling performance of wind catchers was further improved with evaporative cooling, achieving temperature reductions of up to 4°C.

In summary, the reviewed studies show that wind catchers are effective in reducing indoor temperature, though evaporative cooling wind catchers significantly increase indoor humidity. Therefore, these systems are more suitable for hot and dry climates, while other climates require dehumidification technologies. Generally, wind catchers can improve IAQ and thermal comfort by approximately 20–40%.

# 4 | Findings

While recent analyses on the performance of wind catchers have mainly focused on internal factors, this study reveals that external factors also significantly influence natural ventilation performance. As illustrated in *Fig. 15*, urban geometry and external obstacles can affect the characteristics of incoming wind to individual buildings. Additionally, wind speed, wind angle, roof shape, and surrounding buildings are all influential parameters on wind catcher performance, as shown in *Fig. 14*.

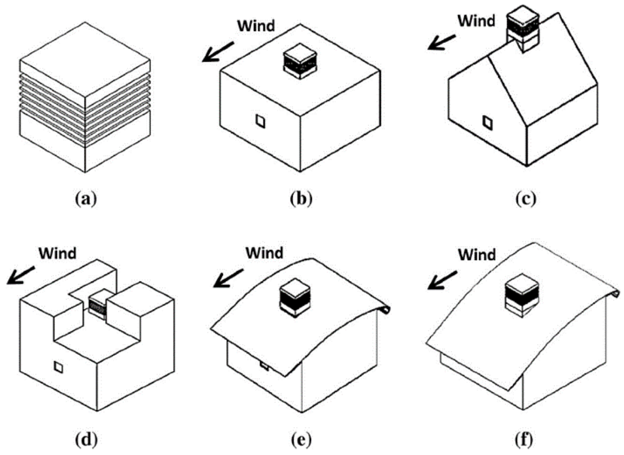



**Fig. 14. The physical models: a. commercial windcatcher, b. flat roof, c. pitched roof, d. narrowed roof, e. curved roof, f. tilted curved roof.**

**Fig.15. Simulation of a building with windcatchers (Inside the red circle) located in an urban environment.**

# 5 | Recommendations

Based on a comprehensive review of wind catcher performance in improving IAQ, thermal comfort, and energy efficiency, the following practical recommendations can serve as effective guidelines for future wind catcher design:

I. Climate adaptation: Design wind catchers that are compatible with the specific climatic conditions of each region (wind patterns, temperature, and humidity).

II. Targeted increase of openings: Increase the number of wind catcher openings to enhance natural ventilation performance and reduce dependency on wind direction.

III. Optimization of cross-sectional shape: Design and optimize the cross-sectional shape of the wind catcher to maximize airflow and pressure difference based on previous studies.

IV. Use of hybrid driving systems: Employ hybrid driving systems (wind, buoyancy force, heat source, or evaporative cooling) to improve performance, especially under variable climatic conditions.

V. Integration with building design: Design wind catchers as an integral part of the building's architecture to ensure aesthetic and functional harmony.

VI. Use of local materials: Utilize indigenous materials for wind catcher construction to reduce costs, increase sustainability, and better adapt to climatic and cultural contexts.

VII. Adding evaporative cooling: In hot and dry climates, incorporate evaporative cooling mechanisms in the wind catcher design to enhance thermal comfort.

VIII. Proper and proportional dimensions: Ensure the wind catcher's dimensions (height, cross-sectional area, and volume) are appropriate and proportional to the building.

IX. Consideration of aesthetics: Pay attention to the visual design of the wind catcher so that it harmonizes with the building facade and urban fabric attractively.

# 6 | Conclusion

This research demonstrated that the three key aspects of building performance—energy consumption, thermal comfort, and IAQ —are strongly interdependent (see *Fig. 16*) and are influenced by both outdoor environmental conditions and the internal and external building design, as follows:

**Energy Interaction with Other Factors**

I. If a natural ventilation system like a wind catcher improves airflow, mechanical cooling needs and electricity consumption decrease.

II. Improved thermal comfort also reduces the use of heating or cooling appliances, thereby lowering energy consumption.

**Indoor Air Quality**

I. Ventilation efficiency (e.g., via wind catchers) and pollutant removal improve when there is effective exchange with outdoor air.

II. Natural ventilation brings in fresh air and removes $CO_2$ and VOCs, improving IAQ to healthier levels.

**Thermal Comfort**

I. Depends on the distribution of temperature, humidity, and airflow.

II. Wind catchers improve these parameters by directing cool outside air inside and exhausting warm air.

**Role of the Outdoor Environment**

I. Climate conditions (wind, temperature, humidity), external obstacles, or outdoor pollution affect both IAQ and thermal comfort.

This diagram indicates that optimizing residential or office building performance cannot focus on just one factor (such as energy use or ventilation); instead, a holistic approach considering the interaction between energy, thermal comfort, IAQ, and their external influencing factors is necessary.

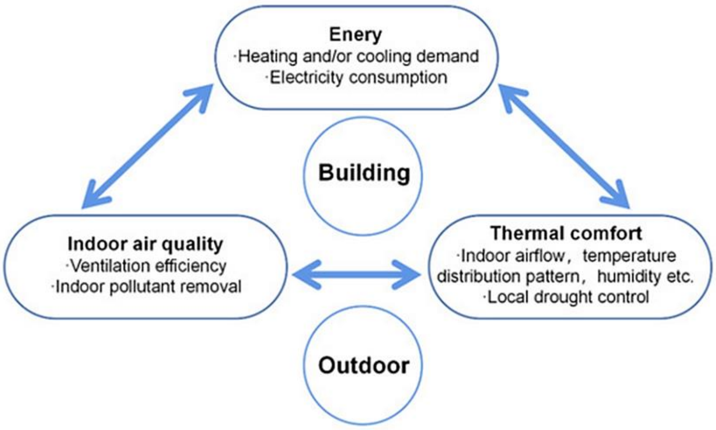



**Fig. 16. Relationships between the occupants, building energy, and indoor environment.**

## Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this manuscript.

## Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Funding

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