




Climate-adaptive windcatcher natural ventilation integrated with passive and low-energy technologies: A review of current and future developments

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ABSTRACT

The integration of natural ventilation systems, such as windcatchers, in modern buildings has garnered interest due to rising energy costs and the need for sustainable practices. Windcatchers have been adapted in many regions to enhance indoor air quality and comfort while reducing reliance on mechanical systems and air conditioners. However, extreme climates, such as hot, humid, and cold conditions, pose challenges to effective windcatcher ventilation. Consequently, passive or low-energy cooling, heating and dehumidification technologies have been developed and integrated into windcatchers to improve thermal performance. Despite extensive research, a comprehensive review synthesizing windcatcher integration with passive and low-energy technologies across diverse climates is lacking. Existing studies often focus on specific elements or singular climatic conditions, leaving a gap in understanding the holistic application and optimization of these systems in various environments. This review addresses this gap by analyzing 147 studies on windcatchers and integrating windcatchers with technologies such as evaporative cooling, earth-air heat exchangers, heat pipes, and phase change materials. It evaluates the performance of these systems in hot and arid, temperate, tropical, continental, and polar climates, offering insights into their effectiveness and challenges. Key findings indicate that windcatchers with evaporative cooling effectively reduce indoor temperatures in hot, arid climates, though water scarcity remains a limitation. Earth-air heat exchangers and passive heat recovery technologies enhance efficiency in temperate regions, while indirect evaporative cooling is promising for humidity management in tropical climates. For continental and polar climates, integrating windcatchers with stoves, heat recovery, and solar thermal technologies is proposed, as traditional designs are inadequate in extreme cold. The review offers tailored recommendations for windcatcher designs across climates, guiding future research.

1. Introduction

With the rising energy prices and the growing concerns about global warming, there is an increasing emphasis on improving energy efficiency across various sectors. The built environment, in particular, plays a crucial role in advancing a sustainable energy economy. The construction and built environment sector is responsible for nearly 40 % of direct and indirect global carbon emissions [1]. A significant portion of this energy consumption, up to 50 %, is attributed to heating, ventilation, and air-conditioning (HVAC) systems [2,3]. Air-conditioning represents one of the fastest-growing energy uses within the built

environment and exerts considerable strain on electricity grids worldwide. For instance, in 2016, approximately 10 % of global electricity consumption was dedicated to cooling purposes [4]. In cities with hot climates, such as Shanghai, cooling consumption can account for up to 40 % of the peak power load [5]. Given that people spend over 80 % of their time indoors, ensuring sufficient ventilation is crucial for both work and living environments. This importance is magnified as the time spent indoors continues to increase [2,6].

Consequently, there is a strong need for sustainable and economical solutions that provide building occupants with optimal indoor thermal comfort and air quality while minimizing the reliance on mechanical

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systems and air conditioners [7]. Among the various technological options available to enhance building energy performance, windcatcher natural ventilation stands out as a particularly attractive solution. Windcatchers have garnered significant research interest due to their ability to supply fresh air and remove heat, moisture, and pollutants from buildings using only natural wind forces and thermal buoyancy [8].

A windcatcher, also known as a wind tower, is a natural ventilation device integrated into rooftop structures that captures wind at higher elevations, utilizing wind pressure and thermal buoyancy to introduce fresh air and expel stale or polluted indoor air, offering functionality similar to mechanical ventilation systems [9–11]. While windcatchers have been commercially used in the UK for over 30 years [12], their origins trace back to the Middle East, where they have been employed in various sophisticated applications for thousands of years [13]. One of the earliest documented examples of traditional windcatchers was found in the Tappeh Chackmaq site in Shahrood, Iran, dating back to around 4000 BC [14,15]. In the UK, thousands of modern windcatchers have been installed in diverse settings, including public buildings, schools, and shopping malls [16,17].

Windcatchers operate by harnessing natural wind forces (Fig. 1). Typically, a windcatcher has multiple openings, allowing it to direct airflow into a building as well as exhaust air out, functioning similarly to a combined wind scoop and chimney. Positive pressure on the windward side drives airflow into the building, whereas negative pressure on the

leeward and other sides aids in extracting polluted indoor air [7,18]. However, natural ventilation through windcatchers alone is often insufficient to provide the required indoor thermal comfort in extreme hot and cold climatic conditions. For instance, in hot and humid climates, high outdoor temperatures and humidity levels, both during the day and night, can exacerbate thermal discomfort for occupants [7,18]. To address this challenge, researchers have been exploring the integration of windcatcher natural ventilation with passive or low-energy technologies, such as solar heating, heat recovery, evaporative cooling, heat transfer devices, and thermal mass. These combined approaches aim to enhance indoor thermal comfort and air quality while minimizing the dependence on air conditioners [19,20].

In desert areas with hot and dry summers, evaporative cooling has proven to be an effective low-energy cooling method, though it is important to consider water resource availability [7,21,22]. Windcatchers can be further optimized by integrating them with a solar chimney to enhance ventilation performance [23]. This combination of evaporative cooling and humidification has been successfully applied in natural ventilation systems using windcatchers assisted by solar-heated exit walls [24]. Moreover, research has explored the integration of earth-air heat exchangers (EAHE) into windcatcher systems [18,25]. This study aims to identify the most effective combinations of passive technologies to provide optimal indoor environments while minimizing environmental impact.

Despite the extensive literature on windcatcher natural ventilation

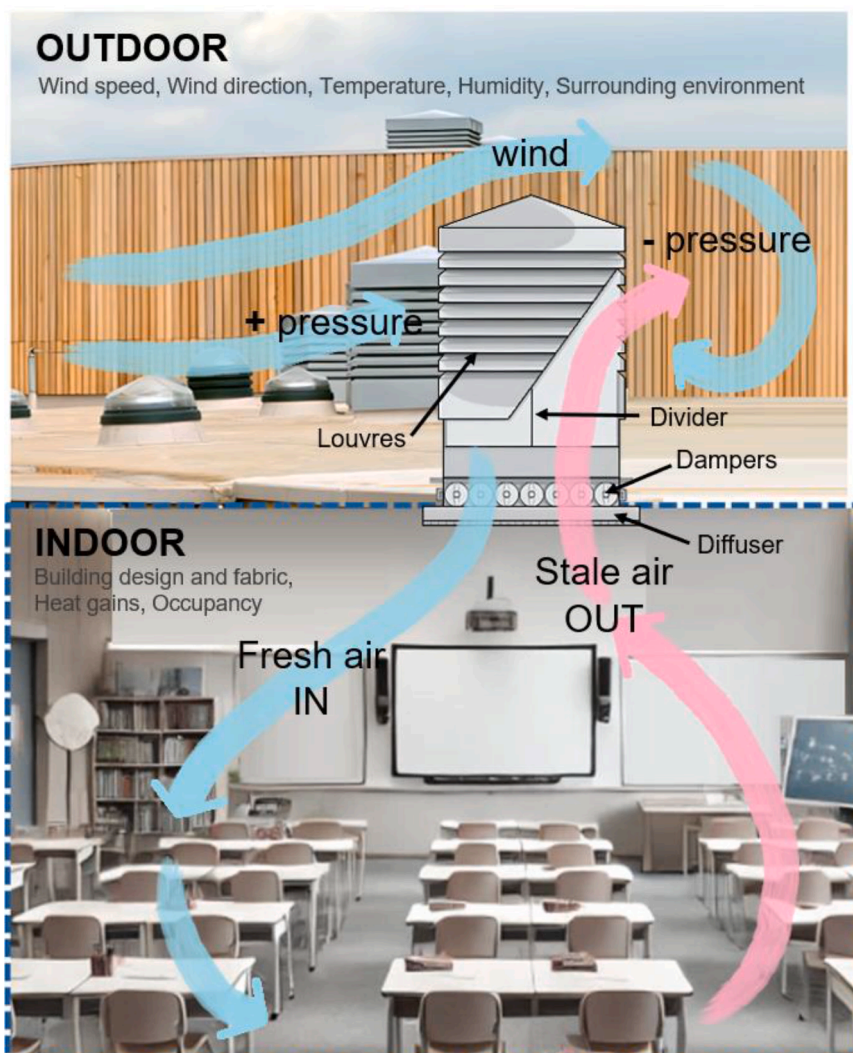


Fig. 1. Operation of a modern roof-mounted windcatcher system and the parameters influencing its performance.

systems and their benefits for sustainable building design, comprehensive reviews that synthesize the integration of passive and low-energy technologies across various climates are limited. Existing reviews often focus narrowly on specific elements of natural ventilation systems, such as windcatchers alone [9,26,27], or on their applications within singular climatic conditions [28]. Additionally, much of the current literature addresses the technological aspects and energy performance of these systems but does not adequately examine their effectiveness in diverse and extreme climatic scenarios [29]. There is a notable gap in detailed comparisons and suitability assessments of different passive and low-energy technologies when combined with natural ventilation systems like windcatchers.

While some studies explore the effectiveness of these technologies in arid or temperate climates, there is a lack of research on their application in tropical or cold climates, where environmental challenges are significantly different. Due to climate change, many temperate regions are now experiencing hotter summers and milder winters, while some traditionally cold regions are also facing hot summers. This shift complicates the use of natural ventilation and passive cooling with windcatcher systems. Researchers and engineers need to develop a comprehensive understanding of potential issues when applying windcatchers in various regions, considering the increasingly unpredictable and extreme weather patterns driven by climate change. This uncertainty affects the wider adoption of windcatcher technology as it raises concerns about its reliability and efficiency in diverse and changing climates.

Thus, this review aims to bridge these gaps by systematically evaluating existing literature on windcatchers and associated passive or low-energy technologies to identify effective combinations suited to various climatic conditions. By providing guidance and practical recommendations, this study seeks to advance the development and optimization of windcatcher systems and associated passive or low-energy technologies, thereby enhancing sustainable building practices. The objectives include a thorough analysis of current studies to understand the prevalence and characteristics of various windcatcher designs, as well as evaluating the

effectiveness of associated low energy/passive heating, cooling, and dehumidification solutions. Additionally, this review will compare the performance of these technologies across different climate conditions by utilizing case studies, experimental data, and theoretical analyses to assess their adaptability and limitations. Finally, the research will propose recommendations for implementing suitable technologies within windcatcher systems to optimize indoor thermal comfort. These strategies particularly focus on enhancing the application of windcatchers in understudied regions such as tropical, continental, and polar areas. The ultimate aim is to extend the utility and environmental benefits of windcatchers to a broader range of global settings, contributing to the wider adoption of sustainable building solutions. The review process is illustrated through the PRISMA chart presented in Fig. 2.

This review followed the PRISMA framework to ensure a transparent and systematic approach to literature selection. In the identification phase, a total of 147 journal articles were retrieved from the Scopus database using the keywords “Wind catcher” and “Windcatcher”, comprising 135 original research papers and 12 review articles. During the screening phase, duplicate entries were removed, and the remaining titles and abstracts were evaluated for relevance to the study’s focus on natural ventilation in buildings. Only peer-reviewed articles published in English were retained at this stage. In the eligibility phase, the full texts of the shortlisted articles were reviewed in detail to assess methodological quality and relevance. Studies were included if they specifically addressed windcatcher technologies within the context of building ventilation and had been published between 2000 and 2025, ensuring a focus on contemporary research. Articles that fell outside this temporal range or addressed unrelated topics were excluded. To minimise bias and enhance the objectivity of the review, the authors independently screened and assessed the literature and jointly synthesised the findings. Finally, in the included phase, the remaining set of studies was confirmed to meet all inclusion criteria. Although the exclusion of some earlier, foundational works is acknowledged, the selected literature provides a robust and representative overview of current practices, regional research trends, and methodological approaches, while also

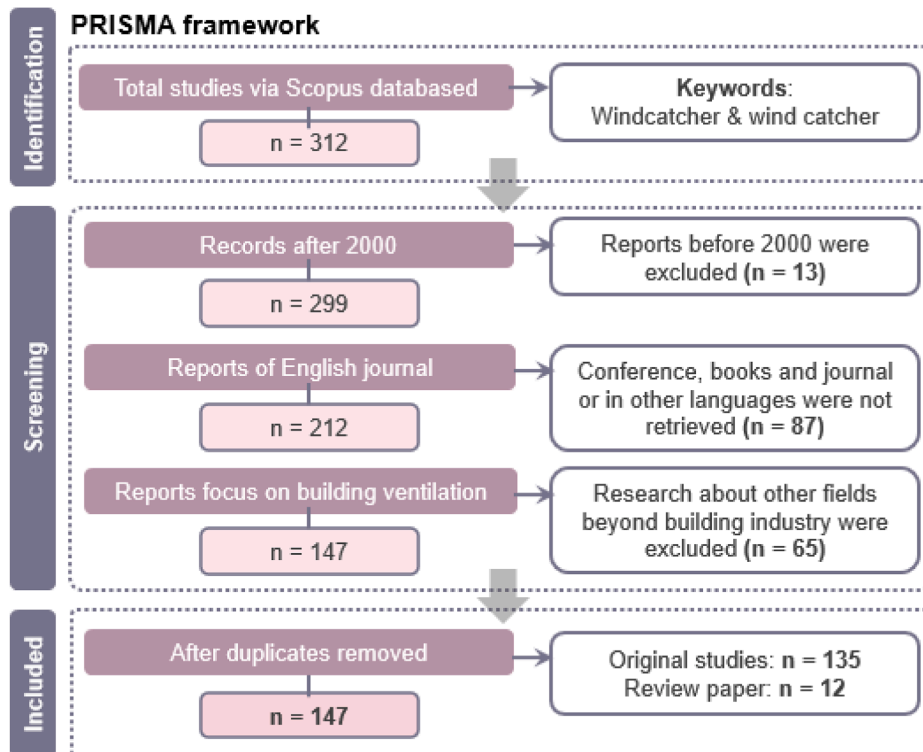


Fig. 2. PRISMA flow chart illustrating the literature screening process used in this review.

highlighting the persistent gap between academic research and the practical needs of the area.

2. State of the art in windcatcher technology research

Previous reviews have described various windcatcher designs based on their geometry and opening configurations [9,26], yet these studies have not adequately linked windcatcher design to their integration with passive or low-energy technologies, which are crucial for addressing diverse indoor thermal comfort requirements and adapting to changing outdoor conditions. Therefore, this section investigates various windcatcher designs and functionalities across different climates, highlighting whether and how these systems are optimized for ventilation, heating, cooling, and dehumidification. We examine how different passive technologies have been integrated with windcatchers and analyze the impact of geometry on their performance. Through a detailed review of existing methodologies and case studies, including computational and field research, this section synthesizes recent advances in windcatcher technology and identifies opportunities for future research.

2.1. Diverse design and functionalities of windcatchers in various climates

More than half of the research on windcatchers focuses on their ventilation performance, reflecting their primary function of facilitating natural ventilation as an alternative to mechanical systems, as illustrated in Fig. 3. Some studies did not specify the type of windcatcher used, and these were included in Fig. 3 for comprehensive analysis. Research addressing the heating and cooling functionalities of windcatchers has also been conducted, with 8 studies focusing on heating and 48 on cooling. This significant disparity indicates that cooling is a more critical function of windcatchers, particularly in regions like the Middle East where they are predominantly studied. Implementing cooling, often

via water spray (evaporative) systems, in current windcatcher designs, is generally more straightforward compared to the utilization of passive or renewable heat sources for heating. Additionally, only one study has investigated passive dehumidification in windcatchers [30], highlighting a significant gap in the research.

Most windcatcher research is conducted in regions with hot and arid conditions, as shown in Fig. 4. In contrast, their potential for dehumidification remains relatively underexplored. The inherent challenge of reducing humidity without significantly raising indoor temperatures makes windcatchers difficult to effectively implement in humid climates. The existing distribution of research emphasizes the multifunctional nature of windcatchers but also highlights the critical need to further investigate and enhance their heating and dehumidification capabilities, alongside continuing advancements in their primary functions of natural ventilation and passive cooling.

Most research on windcatchers, particularly regarding natural ventilation and passive or low-energy cooling, has predominantly focused on applications in the Middle East. Single-sided and two-sided windcatchers are the most commonly studied types in these regions. In contrast, research into passive heat recovery has been largely driven by UK-based groups investigating four-sided tower windcatchers. These differences in windcatcher configurations for passive heating and cooling are primarily due to the distinct airflow requirements of the associated passive or low-energy technologies and the influence of local wind characteristics, including speed, direction, and variability. For instance, Earth-Air Heat Exchangers (EAHE) and evaporative cooling systems can be efficiently integrated into single-sided windcatchers by pre-cooling the incoming air, thus making a single inlet sufficient for their operation. Conversely, passive heat recovery systems involve transferring waste heat from exhaust air to incoming fresh air, necessitating windcatcher designs with multiple openings, such as two or four-sided types, to effectively facilitate this process. Windcatchers vary significantly in shape, cross-sectional design, number of openings, and

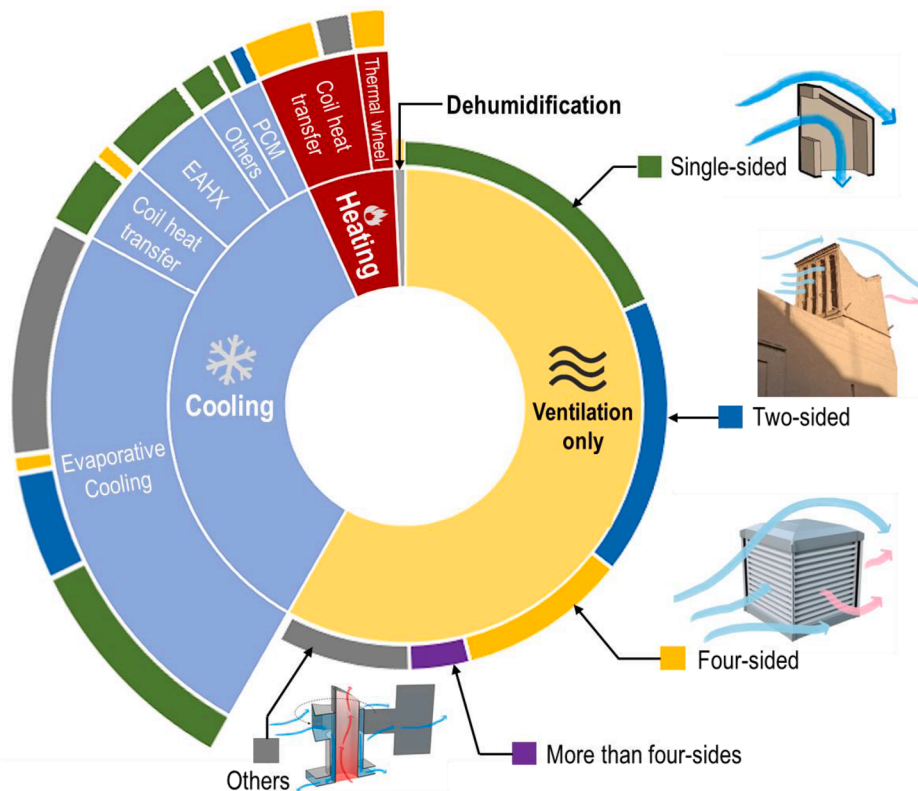


Fig. 3. Overview of studies on windcatchers investigated in this review, categorized by their primary functionality: ventilation, heating, cooling, and dehumidification.

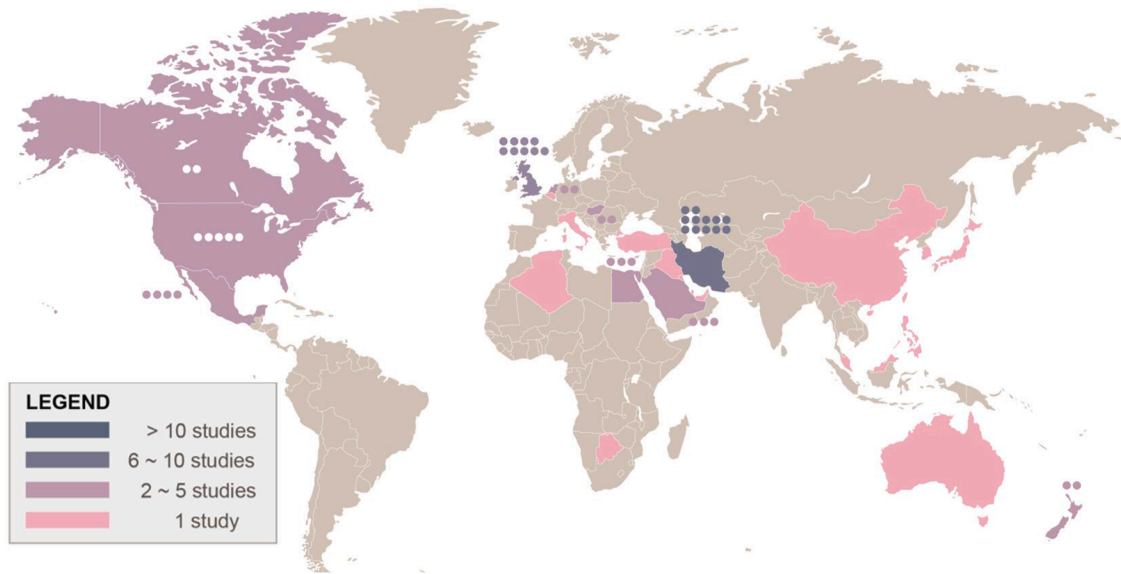


Fig. 4. Global map showing the geographical distribution of windcatcher research.

height to suit specific geographic locations, building types, and prevailing wind conditions [31,32]. For example, areas with consistent wind directions typically use windcatchers with fewer openings to effectively channel airflow, whereas regions with variable wind directions adopt designs featuring multiple openings to capture air from various angles. In dusty environments, taller windcatchers are utilized to elevate air intakes above dust-laden zones. Windcatchers are commonly classified according to the number of openings (single, two, four, six, or eight-sided) and by their footprint shapes (square, rectangular, circular, or hexagonal) [33,34]. Fig. 5 illustrates the proportion of each windcatcher type examined in existing literature. In this figure, "rotary scoops" refer to windcatcher designs with rotating or mechanically

controlled openings, while the "Others" category includes studies assessing multiple windcatcher types with varying numbers of openings [35].

Some windcatchers have a single opening dedicated to supplying fresh air, which necessitates the use of windows or additional openings as air outlets [36]. Windcatchers with multiple openings typically provide greater efficiency, as they can capture airflow from various directions [37]. As previously discussed, in multi-directional windcatchers, positive pressure on the windward side drives the supply airflow, whereas negative pressure on the leeward side facilitates extraction of polluted air [7]. Maximizing the pressure difference between inlet and outlet openings can significantly enhance windcatcher

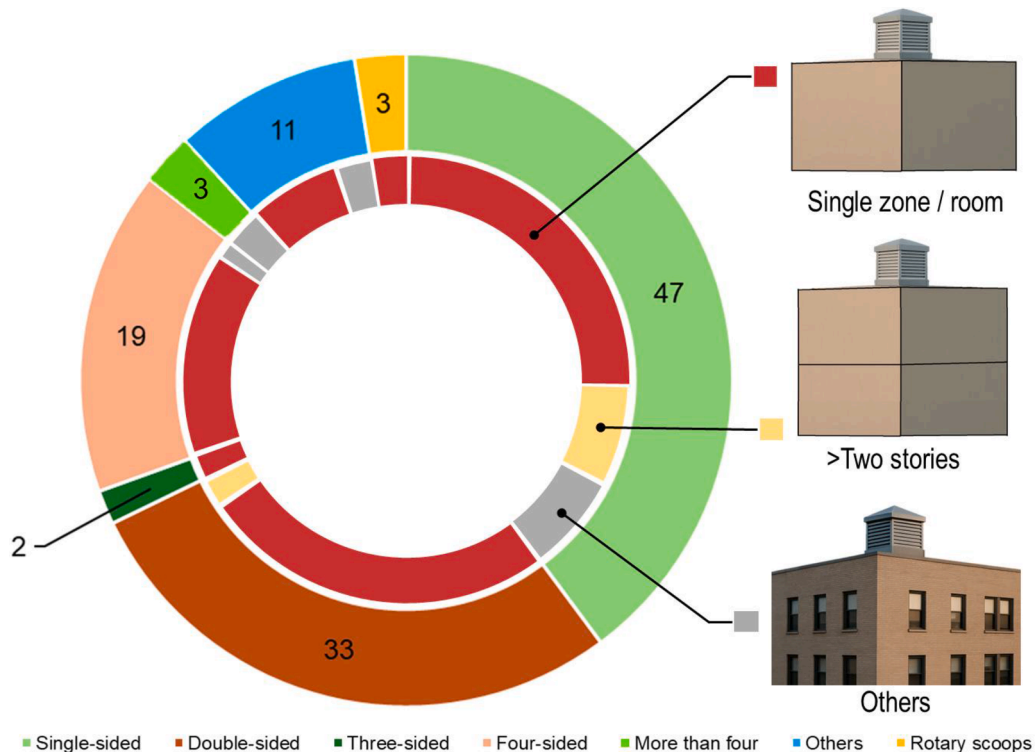


Fig. 5. Classification of windcatchers examined in this review according to their number of openings and associated building types.

efficiency, resulting in improved indoor air quality [38,39]. Several studies have specifically investigated the influence of enlarging inlet or outlet sizes on windcatcher ventilation performance. Varela-Boydo et al. [40] found that expanding the outlet area beyond approximately four times the internal duct area had limited benefits, suggesting strategic rather than maximal sizing. Montazeri and Montazeri [41] reported significant airflow gains up to an outlet size about 1.6 times the inlet area, with minimal improvement thereafter, emphasizing careful outlet positioning to prevent short-circuiting. Cruz-Salas et al. [42] showed that larger, rectangular ducts improved airflow distribution over square ducts. Li et al. [43] demonstrated a 12 % ventilation improvement by increasing wind scoop height from 200 mm to 300 mm, with marginal gains beyond this point. These findings highlight the importance of strategically optimized openings.

Excluding review articles and studies that did not specify the number of openings, a total of 118 studies were analyzed in terms of windcatcher opening configurations. Among these, 47 studies (40 %) examined single-sided windcatchers and the passive technologies integrated with them (Fig. 5). Single-sided windcatchers have a simpler design with only one opening, reducing complexity. For instance, one study integrated an evaporative cooling system with a single-sided windcatcher to pre-cool supply air, successfully enhancing thermal comfort hours from 76 % to 100 % [44]. Two-sided windcatchers, studied in 33 cases (28 %), utilize two openings to separately capture and extract air, featuring a straightforward design that supports the integration of passive technologies such as evaporative cooling systems. Some of these designs employed separate inlet and outlet channels to promote effective cross-flow ventilation [45,46]. However, other configurations were found to be less effective due to suboptimal placements of inlet and outlet openings, potentially causing poor indoor air circulation and short-circuiting of airflow [47,48]. The effectiveness of two-sided windcatchers can be enhanced by introducing additional openings, such as windows. Moreover, airflow distribution and circulation within rooms can be further improved by integrating an anti-short circuit device (ASCD), which ensures air circulation inside the room before being exhausted [47,48].

Fig. 5 also shows the building geometries employed in windcatcher research, highlighting a significant methodological emphasis on simplified models. The total number of studies classified by windcatcher type differs from the total classified by room type, as all 135 studies specified the room type investigated, whereas only 118 studies identified the type of windcatcher examined. The overwhelming majority (80.7 %) analyzed windcatcher performance in isolated, single-room settings, usually simplified or idealized box-shaped rooms, across experimental, numerical, and field-based methods. Although these simplified studies contribute valuable fundamental knowledge, they do not consider the significant impact of internal partitions on natural ventilation dynamics in real-world buildings, as highlighted in reference [49]. This limitation is underscored by the observation that only a small portion of the research (14 out of 135 studies) evaluated windcatcher performance within more realistic building layouts that include multiple stories or internal walls dividing separate rooms. Consequently, while existing literature provides essential baseline insights into idealized conditions, there remains a critical need for additional research focused on windcatcher effectiveness within complex, partitioned interiors to enhance the practical relevance and applicability of findings.

Very few studies have investigated three-sided windcatchers and their evaporative cooling capabilities, with notable examples being a field test and CFD analysis conducted on evaporative wind towers in Madrid [50]. Similarly, research examining ventilation and passive or low-energy technologies in four-sided windcatchers is also limited, accounting for only 16 % of studies. Although increasing the number of openings reduces sensitivity to wind direction, it also decreases maximum ventilation efficiency. Four-sided windcatchers generally exhibit lower maximum efficiency compared to two-sided windcatchers with equivalent opening areas, while windcatchers with six or more

openings demonstrate even lower peak efficiencies [51]. Therefore, under identical environmental wind speeds and favorable wind conditions, windcatchers with fewer openings typically achieve higher ventilation rates.

Moreover, having more openings complicates the integration of passive or low-energy technologies due to varying configurations for air supply and extraction channels. The constantly changing wind direction around buildings [52] significantly influences both ventilation performance [36,53–55] and thermal performance [23,28].

Single-sided windcatchers, in particular, perform effectively in locations with consistent and predominant wind directions but perform poorly under variable wind conditions [9]. Urban environments, characterized by densely packed high-rise buildings, typically experience complex and unpredictable local wind conditions [56]. Thus, evaluating ventilation and thermal performance using fixed wind conditions, such as those employed in wind tunnel experiments and CFD simulations, is often insufficient for accurately predicting real-world performance under variable conditions [57]. For instance, when integrating passive cooling and heating technologies into multi-directional windcatchers [12,58], it is essential to account for airflow direction variations within the air channels [43].

Fig. 6 illustrates three scenarios involving passive cooling devices installed on the windward side, leeward side, and on both sides of a windcatcher. When a passive cooling device is installed only on the windward side, its effectiveness depends entirely on the wind consistently approaching from that direction. A change in wind direction can lead to the supply air not being cooled, while cooled return air exits the building unused, wasting cooling potential. Installing passive cooling devices on both sides can mitigate this issue, but still suffers in efficiencies, as cooled air on the return side exits without fully benefiting the indoor environment. Therefore, a multidirectional windcatcher design must ensure stable and properly directed airflow to effectively integrate passive heating and cooling technologies [59,60].

2.2. Methodologies in windcatcher research

The investigation methods used in windcatcher studies within this review are illustrated in Fig. 7. For example, 26 research studies employed both CFD and experimental methods, while 18 studies relied solely on experimental investigations. Over half of the reviewed studies utilized computational fluid dynamics (CFD) to analyze windcatcher performance, often combining CFD with experimental testing.

CFD provides detailed insights into fluid flow and heat transfer, facilitating windcatcher optimization under various environmental conditions and allowing for the exploration of multiple design scenarios cost-effectively [61]. The accuracy of CFD is enhanced through validation against experimental measurements, which provide reliable benchmarks under controlled conditions that are difficult to achieve in real-world experiments [60].

Although CFD is a powerful tool, it can struggle to accurately model windcatcher systems that incorporate complex elements such as earth-air heat exchangers, heat pipes, or dehumidification units. Accurately representing these complex, coupled heat- and mass-transfer processes in a constantly changing outdoor climate is challenging, and variables such as shifting wind directions and fluctuating temperatures amplify the uncertainty. As a result, most experimental work and CFD studies have assessed windcatcher performance under steady, idealized wind conditions. Field investigations remain scarce, yet they show that real-world operation is far less stable [57]: surrounding buildings, irregular winds, and temperature swings can impact the efficiency of both windcatchers and any integrated passive or low-energy technologies.

Field testing is therefore essential. Empirical measurements not only validate CFD predictions but also expose performance under the full spectrum of real-world climates, helping designers fine-tune both stand-alone windcatchers and hybrid systems. An integrated workflow that combines CFD, laboratory experiments, and long-term field monitoring

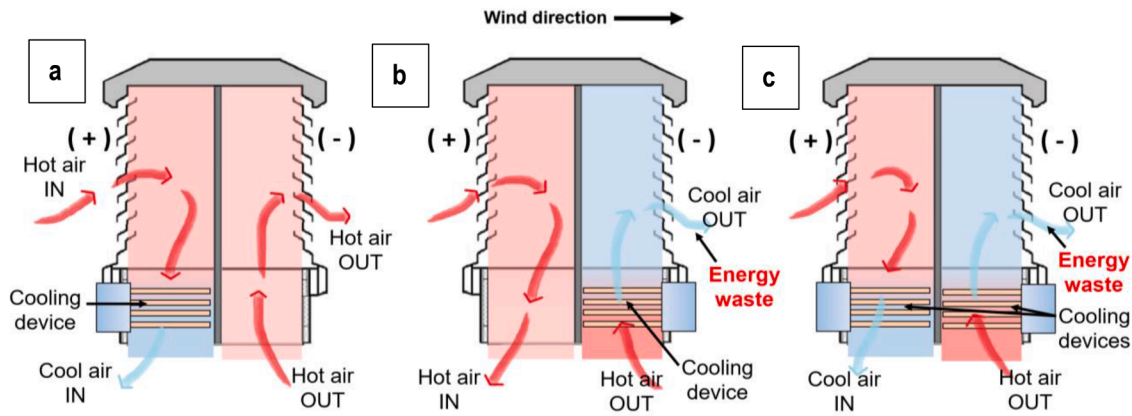


Fig. 6. Operation of a multi-directional windcatcher when the cooling device is in the (a) windward channel, (b) in the leeward channel, and (c) both channels.

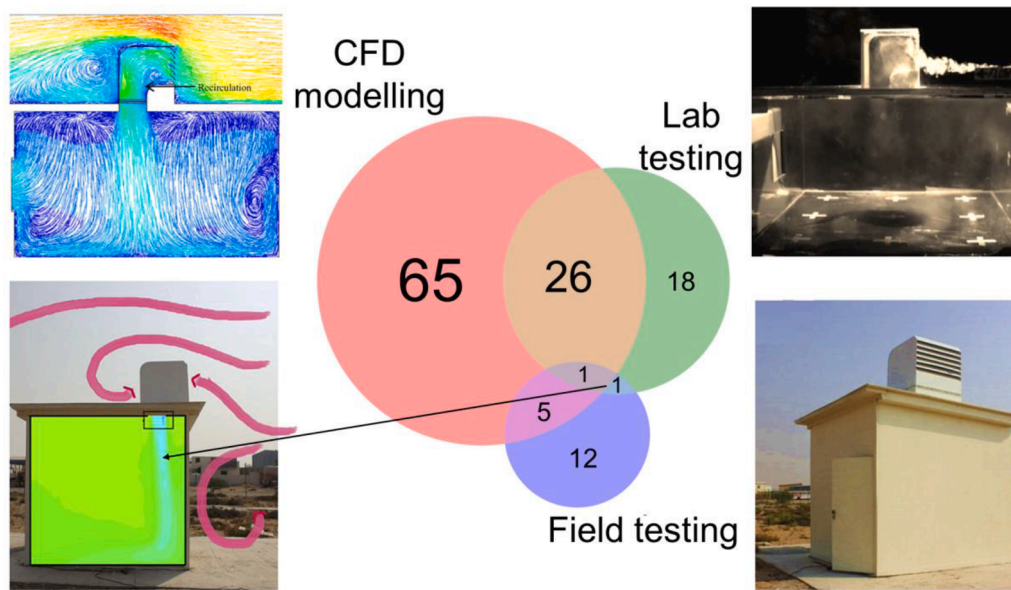


Fig. 7. Distribution of research methods employed in windcatcher studies.

would greatly improve model accuracy and boost confidence in windcatchers as reliable, energy-saving solutions. Yet, to date, only a few studies have employed all three methods simultaneously [59], highlighting the necessity for more comprehensive research adopting this integrated approach.

Current studies have largely focused on demonstrating windcatchers' capabilities for passive ventilation and cooling through experimental and CFD-based evaluations. Yet, as an integral building energy technology, assessing their annual energy-saving performance and carbon emission reductions is critical for their broader adoption and effective implementation. For instance, earth-air heat exchangers, common in Passive House designs, have their efficiency and impact routinely assessed using established tools such as the Passive House Planning Package [62]. Similarly, windcatchers could benefit significantly from advanced simulation combined with comprehensive, long-term field studies to clarify their practical effectiveness and identify opportunities for improvement.

Moreover, the absence of extensive, long-term evaluations of windcatchers' energy-saving potential limits their ability to access carbon finance, a valuable mechanism that supports technology adoption and development through green financial incentives [63]. Recognizing windcatchers as an effective passive solution for reducing energy consumption and emissions could enable their integration into carbon

finance schemes, driving further innovation and wider implementation [64]. A parallel example can be seen in China's photovoltaic industry, where evaluating and crediting carbon emission reductions has accelerated growth by 55% year-on-year in 2023, underpinned by supportive carbon finance policies [65]. Adopting a comparable approach could similarly unlock windcatchers' full potential in global sustainable architecture initiatives.

3. Passive and low-energy technologies integrated with windcatchers

Passive and low-energy technologies integrated with windcatchers have been increasingly studied for their potential to enhance energy efficiency and sustainability in built environments. The solar chimney, for instance, harnesses solar radiation to heat air, creating buoyancy-driven airflow that enhances natural ventilation through a windcatcher [23]. Evaporative cooling, which reduces air temperature through water evaporation, is another passive strategy effective in hot, dry climates [24]. The EAHE utilize the earth's thermal inertia to precondition air, providing passive heating or cooling [62]. Additionally, heat recovery systems using heat pipes or thermal wheels can transfer heat between supply and return air, enhancing the energy efficiency of windcatchers [18]. Moreover, phase-change materials

(PCMs) integrated into windcatchers improve thermal performance by decoupling ventilation and cooling cycles, thus enhancing indoor thermal comfort. These integrated passive technologies offer a robust approach to creating sustainable indoor environments.

3.1. Solar chimney

A solar chimney is a passive ventilation device that drives airflow by heating air inside a vertical shaft. The shaft's inner surfaces or a glazed collector attached to it are finished in dark, high-absorptance materials that capture solar radiation. As this air warms, its density drops, creating buoyancy that pulls it upward and out of the chimney; cooler outdoor air is simultaneously drawn in through low-level openings to replace it. Solar chimneys work best when their collector surfaces receive strong, direct sunlight, typically on a south-facing façade in the Northern Hemisphere, because greater solar gain intensifies the stack effect and boosts ventilation. The continuous upward flow they produce can ventilate a space effectively and, under the right conditions, reduce or even eliminate the need for mechanical fans [66].

Combining a windcatcher with a solar chimney can significantly enhance ventilation and cooling performance [67]. Research has demonstrated that this integration can save approximately 90 % of ventilation energy during peak working hours in warm and arid climates, even when natural wind conditions alone are insufficient [23]. When the wind speed is too low to generate a sufficient fresh air supply, the solar chimney can take over, forcing airflow and overcoming the windcatcher's limitations in low wind conditions [68]. This synergy between the two systems ensures reliable and efficient ventilation, enhancing indoor air quality and thermal comfort.

In hot climates, integrating solar chimneys with windcatchers is effective due to abundant solar radiation, generating significant airflow. However, careful design and integration of evaporative cooling or other strategies are needed to prevent indoor overheating. In cold climates, the potential for space heating using windcatchers with solar chimneys is less explored. The main challenge is balancing ventilation with heating needs. Advanced control strategies and integration with passive heating technologies like EAHEs are required for efficient operation. In humid climates, integrating dehumidification into windcatcher systems combined with solar chimneys is essential. High humidity impacts comfort, and without adequate moisture control, warm, moist air delivered by the windcatcher can exacerbate thermal discomfort. For example, incorporating desiccant materials to absorb moisture and PCMs to buffer temperature swings, alongside design measures that prevent excessive outdoor moisture intake, can potentially address these issues.

Combining solar chimneys with windcatchers is adaptable across climates, requiring specialized designs such as evaporative pads for hot-arid zones, heat pipes or pre-warmers for cold climates, and desiccant and PCM for humid regions. Crucially, further research involving long-term field data, adaptive-control algorithms, and quantification of energy and air quality impacts is essential for validating these designs under real-world conditions.

3.2. Evaporative cooling

Evaporative cooling systems are frequently employed in building designs to reduce ambient air temperature through water evaporation [69,70]. There are two primary types of evaporative cooling: direct and indirect. Direct evaporative cooling involves direct contact between the incoming air and water, lowering air temperature but increasing its humidity. By contrast, indirect evaporative cooling uses a heat exchanger so that the supply-air stream is cooled without gaining moisture [71], making it the preferred option, though not the only one, for humid climates. Most research to date, however, has concentrated on the simpler direct-evaporative approach.

In natural ventilation systems employing windcatchers, hot, dry air is

passed over a wetted surface such as a wetted column [72] or a water spray system [23]. This interaction causes water to evaporate, absorbing heat from the airflow and thereby supplying cooler air. For instance, the supply air temperature can drop significantly, between 7.8 and 18.5 °C [72]. It should be noted that in the study [72], the reported results were based on measurements at the windcatcher's outlet openings rather than from inside the occupied room itself. In contrast, studies such as [23] and [66] explicitly evaluated the impact of direct evaporative cooling systems on the indoor environment. Specifically, the study by [23] analyzed the combined effects of a water spray system integrated within a windcatcher paired with a solar chimney. This research utilized both experimental scale models and CFD simulations to examine the cooling potential and airflow distribution, verifying significant cooling effects and enhanced airflow rates within interior building spaces. Results indicated temperature reductions of up to 5.2 °C. However, this particular study did not investigate droplet transport or moisture propagation beyond the tower outlets into external environments or through complex indoor configurations.

Conversely, studies such as [45,52] employed CFD simulations that explicitly modeled water droplet transport from spray nozzles located near windcatcher inlets. These analyses demonstrated how cooled and humidified airflow effectively extended beyond the windcatcher outlets, penetrating deeply into interior spaces, confirming both cooling and moisture propagation within more complex building configurations.

Indirect evaporative cooling has also been examined in depth, particularly in the study [73], where the focus was explicitly placed on indoor environments. The study demonstrated stable indoor temperatures (~24.8 °C), humidity control (43–58 %), while achieving up to 70 % operational cost reduction compared to conventional cooling. This indirect method effectively separates moisture from the indoor air, making it ideal for humidity-sensitive climates.

While evaporative cooling systems offer substantial benefits, such as high energy efficiency compared to traditional air conditioning and beneficial humidification in arid climates, they face certain challenges. Significant water consumption required by these systems can be problematic in regions where water scarcity is prevalent. Furthermore, regular maintenance is essential to prevent mold and bacterial growth, including Legionella [74,75]. Moreover, their efficiency can diminish under extremely humid conditions [76]. Most applications of windcatcher-evaporative systems have focused on hot-dry climates, leaving a limited understanding of their long-term viability in temperate regions that increasingly experience hot, humid summers. Addressing critical questions around humidity impacts, water consumption, and Legionella risk requires extensive field studies and dynamic modelling to optimize these systems across diverse climatic conditions.

3.3. Earth-air heat exchanger (EAHE)

EAHE are energy-efficient technologies applicable for a wide range of climatic conditions [62]. EAHE systems utilize the thermal mass of the ground to precool or preheat incoming supply air before it enters a building [28]. At a few meters below ground, soil temperature remains relatively stable throughout the year, while ambient air temperature fluctuates seasonally and daily [77].

Combining a windcatcher with an EAHE can further enhance a building's ventilation efficiency and indoor environmental quality. The integration of an EAHE with a windcatcher has been shown to reduce carbon dioxide emissions by up to 20 kg/m² [25]. A windcatcher aids in driving air circulation by utilizing wind [78] and buoyancy forces [79] to draw air into or out of the building. By routing air through the EAHE before it enters the building, incoming air is thermally conditioned, reducing the energy load of supplementary heating and cooling equipment.

The integration of windcatchers with EAHEs presents several advantages. By utilizing the stable temperatures found underground, the EAHE system can provide temperature moderation, leading to improved

indoor thermal comfort and reduced reliance on mechanical HVAC systems. For instance, buildings using this system can experience a temperature drop of up to 13 °C [80]. However, integrating EAHEs with windcatchers also poses challenges. Extensive underground ductwork is required, increasing construction costs and complexity. The performance of the EAHE can be affected by soil moisture levels and thermal conductivity, which vary based on geographical location. Regular maintenance of the underground ducts is necessary to prevent blockages and sustain long-term operational efficiency, incurring ongoing costs which should also be factored into life cycle analysis [81,82].

Additionally, careful design is needed to ensure the EAHE and windcatcher systems complement each other. This includes optimizing the placement and depth of the underground ducts and ensuring the windcatcher can drive airflow through the EAHE even during low wind speed periods. In calm conditions, the buoyancy-driven stack effect can facilitate airflow through the EAHE; however, exceptionally long or high-resistance duct runs might require a small auxiliary fan to sustain consistent air movement. The combination of EAHEs with windcatchers offers a promising solution for improving indoor thermal comfort and reducing building energy consumption. Future work should focus on climate-specific optimization, for example, refining duct length-to-diameter ratios for wet versus arid soils, testing adaptive controls that switch between wind-driven and buoyancy-driven, and collecting multi-year field data to verify long-term thermal performance and maintenance needs.

3.4. Heat recovery device

Heat recovery systems are vital for energy conservation in buildings, capturing and reusing waste heat to enhance thermal efficiency and reduce energy consumption [83]. A case study in the UK demonstrated that integrating heat recovery into natural ventilation systems can effectively provide fresh air while consuming minimal energy, resulting in a satisfactory thermal environment throughout the year [84]. In windcatcher natural ventilation systems, common heat recovery technologies include heat pipes [85–87] and rotary thermal wheels [83,88]. Heat pipes are particularly suitable for wind-driven systems due to their inherently low airflow [89]. Studies have shown that integrating heat pipes within windcatcher systems can increase supply air temperatures by 2.8 °C [87] to 4.5 °C [86]. Rotary thermal wheels represent another effective heat recovery technology, capable of enhancing supply air temperatures by 3 °C [88] to 3.7 °C [83].

The effectiveness of heat recovery systems varies depending on climate conditions [90]. In colder and temperate climates, they capture and reuse exhaust heat to warm incoming air during winter. However, during summer, these systems may inadvertently increase indoor temperatures when cooling is needed. This necessitates bypass mechanisms or seasonal adjustments to prevent overheating during warmer months [91]. Introducing heat recovery systems adds airflow resistance, reducing windcatcher efficiency [92]. Minimizing resistance while maximizing heat recovery is essential, involving low-resistance pathways and optimal placement of heat recovery units [93]. For example, researchers tried to use heat pipes in the heat recovery system to achieve a 50 % heat recovery efficiency with 1 Pa pressure loss [94].

Regular maintenance is crucial, including checking for leaks and cleaning heat exchangers, especially in urban areas with high levels of particulate pollution, which can increase operational costs. Integrating heat recovery systems with windcatchers can raise initial construction costs and complexity, requiring additional space and structural considerations, particularly in retrofitting projects. Despite these challenges, the benefits of improved thermal efficiency and reduced energy consumption make this integration a promising solution for windcatchers.

3.5. Phase change material (PCM)

PCMs store and release large amounts of energy, much more than

concrete [95], during their transition between solid and liquid phases, providing significant thermal mass without occupying much space in the building [95,96]. Integrated into building structures, PCMs absorb excess heat during the day when external temperatures are high through the melting process, thereby lowering indoor air temperatures. Conversely, at night or when external temperatures drop, the stored heat is released as the PCMs solidify, pre-warming the cooler incoming air. Installing PCMs in the inlet channel of a windcatcher can reduce indoor air temperature by up to 2.7 °C [97], contributing to passive cooling and lower energy demand in buildings [98]. This integration can precondition the supply air in regions with significant daily temperature fluctuations, maintaining indoor air temperatures throughout a typical seven-hour workday [99].

The integration of PCM into building facades can be limited in effectiveness due to low convection heat transfer [100], which diminishes their ability to absorb and release heat efficiently when relying solely on natural airflow. Integrating PCMs with windcatchers also presents challenges. The amount of PCM needed for extended cooling depends on its specific heat capacity, the building's thermal load, and external climate conditions. In hot, dry climates, substantial day-night thermal swings justify larger PCM volumes to accommodate the high cooling loads. In temperate climates, a balanced amount of PCM often suffices to smooth out temperature variations. In humid climates, where temperature differences between day and night are modest, PCM efficiency is reduced, requiring more PCM or supplementary systems and humidity control measures.

Additional challenges include PCM thermal performance degradation over time, high initial costs, and regular maintenance needs, such as monitoring for leaks and material degradation. Integrating PCMs into windcatchers adds design and construction complexity, requiring proper placement and insulation to maximize benefits without compromising structural integrity. Despite these challenges, PCMs can enhance energy savings and thermal comfort, making them a valuable addition to windcatchers. Moreover, the flammability of the organic PCMs is also a challenge which needs to be considered in the application of PCM in buildings [101]. Because most organic PCMs are combustible, they should be housed in a sealed plenum or service void, physically separated from occupied rooms, to satisfy fire-safety requirements [101]. Further research is essential to address these issues and optimize PCM use in different climates.

3.6. Passive and low-energy dehumidification

Maintaining indoor air humidity at suitable levels is crucial for indoor air quality and occupant comfort [102]. To minimize the risk of microbial growth, indoor relative humidity should be kept below 65 % [103]. While natural ventilation is often used to control indoor moisture; however, in regions with high outdoor humidity, particularly during hot summer months, this method alone may be inadequate and can even contribute to increased building cooling loads. For instance, Passivhaus standards recommend indoor air moisture content below 12 g/kg, roughly equivalent to 60 % relative humidity (RH) at 25 °C [104].

In tropical and hot, humid regions, outdoor air often contains high levels of moisture, particularly during the rainy season or in coastal areas, making it challenging to maintain the desired indoor humidity and temperature through natural ventilation alone. When outdoor air moisture content exceeds the recommended levels, introducing it indoors via natural ventilation can elevate indoor humidity instead of reducing it, leading to thermal discomfort and promoting mould growth. This high humidity also increases the cooling load on buildings, as air conditioning systems must work harder to dehumidify and cool the air, leading to higher energy consumption and operational costs [105].

To address these challenges, passive and low-energy dehumidification systems have been developed. These systems utilize solar energy and desiccants, like silica gel, to effectively reduce moisture from incoming air. For example, integrating a rotary desiccant wheel coated

with silica gel into a four-sided windcatcher demonstrated promising potential for effectively reducing humidity under controlled laboratory conditions simulating highly humid outdoor air, while maintaining a sufficiently low pressure drop suitable for passive ventilation systems [30]. By absorbing moisture from incoming air before it enters the building, these systems can precondition the supply air, reducing reliance on mechanical HVAC systems and improving energy efficiency. This approach is particularly beneficial in regions with significant daily temperature and humidity fluctuations, helping to maintain indoor comfort and air quality.

However, introducing cooling mechanisms within windcatcher system can exacerbate moisture issues. When air is cooled, its moisture-holding capacity reduces; without proper drainage or moisture control, the resulting condensation can drive indoor humidity back up rather than down [69]. In humid climates, this can introduce more moisture indoors, complicating dehumidification. Therefore, integrating cooling with windcatchers requires careful design to ensure effective moisture management, possibly incorporating advanced dehumidification technologies alongside cooling to maintain optimal indoor air quality and comfort. Additionally, the integration of dehumidification systems can increase initial construction costs and complexity and necessitate regular maintenance to ensure effectiveness and longevity.

3.7. Comparison of different windcatcher passive and low-energy technology integration

Table 1 provides a comparative analysis of various windcatcher types, highlighting their sensitivity to wind direction, the integration of passive or low-energy technologies, advantages, disadvantages, and suitable climates. This comparison is crucial for understanding how different windcatcher designs perform under varying environmental conditions and technological integrations, helping inform the selection and optimization of sustainable ventilation solutions in building designs.

Single-sided windcatchers are highly cost-effective and straightforward, making them ideal for hot and dry climates with consistent wind directions. They integrate well with earth-air heat exchangers, evaporative cooling, and PCMs, enhancing their performance by preconditioning the supply air and reducing reliance on mechanical HVAC systems. Because a single-sided windcatcher only performs well when its intake is windward, it must be paired with a reliable exhaust route, such as an open window or roof stack, to maintain cross-flow. This added requirement can make the design less effective on sites where wind direction frequently shifts. Two-sided windcatchers, also sensitive to wind

direction, offer high ventilation rates in hot and arid climates where wind patterns are more predictable. They integrate well with evaporative cooling systems but can suffer from inconsistent performance in regions with fluctuating wind directions. Four-sided windcatchers provide a balanced solution with moderate sensitivity to wind direction, making them suitable for regions where wind variability is more manageable. They can integrate passive heat recovery systems such as heat pipes and rotary thermal wheels, which improve thermal efficiency. However, their more complex design and higher costs require careful planning and maintenance.

Windcatchers with eight or more openings are designed for areas with highly variable wind directions. They offer flexibility in capturing wind from multiple angles but generally have lower ventilation rates compared to simpler designs. Their complex integration with passive technologies poses challenges, and they can incur higher construction and maintenance costs. The appropriate passive technologies and windcatchers need to be selected based on the demand of occupants and the local climate, including air temperature, humidity, and wind conditions throughout the year. This ensures that the chosen system meets the specific needs of the building’s environment and its users, promoting energy efficiency and indoor comfort. Table 1 highlights that each windcatcher type has unique strengths and weaknesses, making them suitable for different climates and applications. The integration of passive and low-energy technologies enhances their performance but introduces complexity, necessitating careful design, implementation, and maintenance to ensure effectiveness and sustainability.

4. Climatic assessment of windcatchers with passive and low-energy technologies

The effectiveness and efficiency of windcatcher technologies vary significantly across different climatic regions due to the unique environmental challenges and requirements of each climate. This section explores the application of windcatchers in various climates, including tropical, arid, temperate, continental, and polar regions, to identify the best practices and potential adaptations needed for optimal performance. By examining the integration of passive and low-energy technologies, we aim to provide an understanding of how these systems can be tailored to meet the specific demands of each climate. The discussion will highlight both the advantages and limitations of using windcatchers in different regions, offering insights into potential improvements and innovative solutions to enhance their application and efficacy.

To classify the research and applications of windcatchers, we apply

Table 1
Comparison of natural ventilation windcatchers with passive or low-energy technologies.

Windcatcher type	Sensitivity to wind direction	Passive or low-energy technology integration	Advantages	Disadvantages	Suitable climates
Single-sided windcatcher [36]	High	<ul style="list-style-type: none"> • Earth-air heat exchanger [78] • Evaporative cooling [106] • PCM [99] 	<ul style="list-style-type: none"> • Low cost • Simple design • High ventilation rate at design wind direction 	<ul style="list-style-type: none"> • Highly sensitive to wind direction, reducing effectiveness in variable wind conditions • Requires a dedicated exhaust path for cross-flow 	Hot and dry climates; areas with consistent wind direction
Two-sided windcatcher [107–109]	High	<ul style="list-style-type: none"> • Evaporative cooling spray or cloth [23] 	<ul style="list-style-type: none"> • High ventilation rate at design wind direction 	<ul style="list-style-type: none"> • Highly sensitive to wind direction, leading to inconsistent performance 	Hot and arid climates; regions with predominant wind direction
Four-sided windcatcher [12,58]	Moderate	<ul style="list-style-type: none"> • Heat pipe for cooling and heat recovery [85–87] • Thermal wheel [83] 	<ul style="list-style-type: none"> • More consistent performance regardless of wind direction 	<ul style="list-style-type: none"> • Integrated passive technologies are sensitive to wind direction • More complex design and higher cost 	Hot and arid climates; Temperate climates; areas with moderate wind variability
Eight-sided or more openings windcatcher [51]	Low	None	<ul style="list-style-type: none"> • Suitable for areas with highly variable wind directions 	<ul style="list-style-type: none"> • Reduced maximum efficiency compared to windcatchers with fewer openings • Complex passive technology integration • Potentially higher construction and maintenance costs due to complexity 	Regions with highly variable wind directions

the Köppen-Geiger climate classification system, which is widely used in geography, ecology, and atmospheric science [110]. This classification system, based on local climate and natural vegetation, provides a clear categorization of weather conditions and their physical implications [111]. The detailed classification is listed in Table 2, and the windcatcher research is categorized as: tropical, arid/dry, temperate, continental, and polar.

4.1. Group A: humid and tropical climates

In tropical and humid climates, it is essential to utilize a ventilation system design that can manage humidity and enhance thermal comfort, often in combination with other methods to achieve lower indoor air temperatures compared to the outdoor environment [114,115]. Windcatcher have the potential to improve IAQ and thermal comfort in tropical regions [116]. However, research into their performance in tropical climates remains limited, primarily due to a prevailing assumption that windcatchers alone may not achieve adequate thermal comfort under such challenging conditions [27]. The inherently hot and humid climate, coupled with characteristically low environmental wind speeds [117], presents significant challenges for wind-driven ventilation systems.

Direct evaporative cooling, effective in hot and arid regions, faces significant hurdles in humid climates [118]. As the cooling performance strongly depends on environmental conditions, the temperature drop by a direct evaporative cooling system might be limited [119] and provide saturated air to the room [69]. For example, research in Malaysia showed that evaporative cooling could only reduce indoor temperatures marginally, from 31°C-35°C to 28.4°C-31.7°C, and the high humidity still caused discomfort for occupants [120]. Additionally, the application of EAHE in tropical climates may offer limited energy savings, as the soil temperature in these regions can often be closer to or exceed the desired indoor comfort levels throughout the year [62].

Studies indicate that while EAHEs can reduce air temperatures to some extent, their effectiveness is heavily dependent on local soil conditions and climatic factors. Therefore, the performance of EAHEs in tropical climates should be carefully evaluated, considering these variables to determine their potential benefits and limitations. Further research and tailored design strategies are essential to optimize EAHE systems for use in tropical environments. Night-time ventilation with appropriate thermal mass is also limited in many tropical climates because outdoor temperatures and humidity levels at night often exceed the thermal comfort range [121,122].

Despite the challenges of using passive technologies to directly cool indoor environments in tropical climates, increasing airflow speed around occupants can enhance thermal comfort [123]. As the thermal comfort can still be achieved in a humid region with a high environmental wind speed [124]. Windcatchers can achieve higher ventilation rates and increase airflow speed at the occupant level (approximately

1.5 m) by harnessing the higher wind speeds above buildings [125]. By preventing heat traps and ensuring better air circulation, windcatchers can help mitigate discomfort for occupants in these environments [126].

Although a small but growing body of research on windcatchers has focused on providing indoor thermal comfort in tropical regions, only a few studies have specified the location or weather data of their research. Table 3 lists the studies that included this crucial location information. These findings underscore the potential of windcatchers to enhance ventilation and thermal comfort in humid and tropical climates, although their effectiveness can vary based on specific local conditions and implementation strategies. Notably, none of these studies explored the integration of dehumidification systems, such as those using desiccants, highlighting an area for further research. Future studies should focus on optimizing windcatcher designs and integrating them with dehumidification and other passive cooling technologies to maximize their benefits in different tropical environments.

The high outdoor humidity in tropical regions and the need for maintaining appropriate indoor relative humidity limit the application of direct evaporative cooling systems [129]. Therefore, indirect evaporative cooling emerges as a viable passive cooling solution in these climates. Indirect evaporative cooling involves both an evaporative cooling process and a heat exchange process, which separates the indoor air from the water evaporation channel to avoid indoor air humidification and bacterial growth [130]. This separation ensures that indoor humidity levels remain acceptable, preventing discomfort from excessive moisture while the air in the evaporation channel can be humidified to 100 % relative humidity to maximize cooling capacity without causing discomfort associated with direct evaporative cooling [130]. However, the system requires mechanical fans to force the humidification process, ensuring sufficient air with lower humidity, which increases electricity consumption.

Integrating indirect evaporative cooling with windcatchers in tropical regions presents several challenges, because of the high humidity [119] and the current evaporative cooling research is insufficient to

Table 3
Windcatcher studies in the hot and humid (tropical) region.

Passive technology integration	Ref	Location/ weather data	Performance
External shading	[126]	Dala City, Yangon Township, Myanmar	Reduces thermal discomfort hours
Windcatcher ventilation only	[125]	Tangerang, Indonesia	1.2 to 1.4 times ventilation rate increase
	[127]	Nagapattinam, Bay of Bengal coast	Indoor airflow around 0.1–1 m/s reduced discomfort
	[128]	Rio de Janeiro City, Brazil	Air circulation increased from under 0.1m/s to about 0.25 m/s in the room

Table 2
Köppen climate classification scheme symbols description [112,113].

1st letter	2nd letter	3rd letter	Ratio of area [111]
A (Tropical)	f (Rainforest)		21.7 %
	m (Monsoon)		
	w (Savanna, dry winter)		
	s (Savanna, dry summer)		
B (Arid/Dry)	W (Arid Desert)	h (Hot)	31.3 %
	S (Semi-Arid or steppe)	k (Cold)	
C (Temperate)	w (Dry winter)	a (Hot summer)	15.9 %
	f (No dry season)	b (Warm summer)	
	s (Dry summer)	c (Cold summer)	
	w (Dry winter)	a (Hot summer)	
D (Continental)	f (No dry season)	b (Warm summer)	24.2 %
	s (Dry summer)	c (Cold summer)	
		d (Very cold winter)	
E (Polar)	T (Tundra) F (Ice cap)		6.9 %

promote the application of evaporative cooling in humid regions [131]. The integration adds complexity to the windcatcher design, requiring regular maintenance to ensure efficient operation, including maintaining the evaporative cooling pads, fans, and heat exchangers. Additionally, the system depends on a reliable water supply, which can be challenging in areas with limited resources [132]. Installation costs are higher due to the additional components required for heat exchange and air separation, and the system typically requires more space, which can be a limitation in densely built environments. Finally, the performance of indirect evaporative cooling can be influenced by specific climatic conditions, necessitating tailored designs for optimal effectiveness [119].

To address the energy consumption issue, solar power can be utilized to run the mechanical fans and pumps required for the indirect evaporative cooling system. By integrating solar panels, the system can generate electricity during the day to power these components. This approach not only minimizes the environmental impact but also utilizes abundant solar energy in tropical regions.

Additionally, passive dehumidification systems can be integrated to manage high humidity levels more effectively. Using desiccant materials within windcatchers can absorb moisture from the air, helping to maintain comfortable indoor humidity levels without the need for additional energy-intensive dehumidification processes. However, these desiccants require periodic regeneration, typically via solar heating, to restore their moisture-absorbing capacity. This integration can further enhance the overall efficiency and effectiveness of the cooling system in humid and tropical climates.

Given these considerations, future research should focus on developing integrated system designs tailored to tropical climates, emphasizing optimization of windcatcher geometry, effective integration of indirect evaporative cooling, and incorporation of passive dehumidification. This integration, especially with solar-powered fans and pumps, could provide cost-efficient cooling solutions particularly suited for tropical regions.

4.2. Group B: hot and arid climates

Many studies consider the Middle East, particularly Iran, as the origin of windcatcher technology [13]. This region provides many examples of traditional windcatcher integration dating back many centuries. These traditional windcatchers were often combined with underground water channels, known as qanats, which helped cool the air before it entered the building. The use of heavyweight materials, such as thick mud bricks, provided thermal mass that helped stabilize indoor temperatures by absorbing heat during the day and releasing it at night. Furthermore, these windcatchers were designed to capture prevailing winds and funnel them into living spaces, enhancing air circulation and comfort. While this region is characterized by a variety of climates, including hot and humid areas, our focus here is primarily on the hot and arid regions. Windcatcher research in this climate represents the largest proportion in this review, providing ample data on windcatchers integrated with passive and low-energy cooling technologies.

In desert areas with hot and dry summers, direct evaporative cooling has been established as an effective passive cooling method, particularly when combined with windcatchers. However, the availability of water resources must be considered [52,68,133]. Studies have demonstrated the effectiveness of evaporative cooling systems in reducing air temperatures in arid regions, such as Yazd City, Iran [46], and Masdar, Abu Dhabi [134], achieving temperature reductions of up to 10 °C. Additionally, a CFD simulation evaluated an evaporative cooling system assisted by a solar chimney in a three-floor building using weather data from Yazd City, Iran, achieving a total cooling capacity of 9 kW [68].

EAHE are also effective in providing cool air in arid regions, where lower soil temperatures a few meters below ground can be utilized. Significant temperature reductions have been recorded, such as a 13 °C reduction in Baghdad, Iraq [80], and a 15 °C reduction in Yazd City, Iran

[135]. In Ouargla, Algeria, a system cooling capacity of up to 30 kW was achieved, with a temperature reduction of up to 20 °C [136]. Another study on EAHE and evaporative cooling under typical hot and arid climate conditions demonstrated a system with a high cooling capacity of up to 10 kW, reducing room temperatures from 35 °C to 28.6 °C [78].

The low thermal inertia of soil compared to water results in higher diurnal temperature variations in arid regions [137], leading to higher daytime and lower nighttime temperatures. This makes PCMs particularly suitable for arid regions, as the latent heat stored in PCMs can be released at night, allowing the passive cooling process to be recyclable during the day. In Iran, installing PCMs in the windcatcher inlet has reduced indoor air temperatures, demonstrating passive cooling potential over a seven-hour daytime period [99].

The research on passive technologies in windcatchers that provided location or weather data in hot and arid regions is listed in Table 4. Most studies in these regions have achieved significant indoor air temperature reductions. Evaporative cooling and EAHE have all shown considerable promise in reducing indoor temperatures and enhancing thermal comfort. The key to their effectiveness lies in careful consideration of local climatic conditions, such as soil thermal properties and diurnal temperature variations, to optimize the design and implementation of these systems. Further research should focus on refining these integrations and exploring new combinations to maximize energy efficiency and indoor comfort in arid environments.

While windcatchers can be effective in enhancing indoor thermal comfort, integrating passive or low-energy cooling technologies is essential to cope with the extreme climates found in arid regions. Various passive technologies have been proposed and evaluated to provide efficient passive cooling in these harsh environments successfully. These technologies enhance the performance of windcatchers, and achieve comfort improvements even during the hottest periods.

Based on the literature, one of the most suitable and widely used passive technologies integrated with windcatchers in arid regions is direct evaporative cooling which provides both cooling and humidification to the supply air by absorbing heat through water evaporation. This process reduces air temperature and increases relative humidity, thereby enhancing indoor thermal comfort. However, water resources in arid regions are often limited, necessitating further research to optimize the application of evaporative cooling systems effectively.

In regions with hot summers and mild to cool winters, the soil temperature can be sufficiently low to provide pre-cooling to supply air,

Table 4

Passive and low-energy technology integration with windcatchers in hot and arid regions.

Passive technology integration	Ref	Location/ weather data	Performance
Evaporative cooling + solar chimney	[23]	Tehran, Iran	4 °C temperature reduction
	[68]	Yazd City, Iran	6–12 °C temperature reduction Cooling capacity up to 9kW
Evaporative cooling	[44]	Kuwait	52.4 % of cooling energy reduction
	[46]	Yazd City, Iran	10–15 °C temperature reduction
	[134]	Masdar Abu Dhabi	10–12 °C temperature reduction
	[138]	Iran	11.3–13.7 °C temperature reduction
	[139]	Kerman Iran	10 °C temperature reduction
	[140]	Ouargla, Algeria	18.6 °C temperature reduction
EAHE	[80]	Baghdad, Iraq	13 °C temperature reduction
	[136]	Ouargla, Algeria	Cooling capacity up to 30kW 20 °C temperature reduction
	[135]	Yazd City, Iran	Reduce T_{room} to 26.6°C at 42°C T_{out}
PCM	[99]	Iran	Temperature reduction over a 7-hour daytime period

making EAHE systems a suitable choice. By integrating EAHE systems with windcatchers, hot summer air can be pre-cooled and mild winter air can be preheated, minimizing thermal discomfort caused by building ventilation. This combination not only enhances the efficiency of the windcatcher but also ensures a more stable and comfortable indoor environment year-round.

Moreover, PCMs offer a viable solution to reduce peak temperatures during the day when diurnal temperature variation is high and nighttime outdoor temperatures are lower than the indoor cooling setpoint. PCMs in the windcatcher can absorb heat from the supply air during the day, lowering its temperature, and releasing the stored heat at night, providing a stable indoor environment. However, the latent-cooling capacity of a PCM layer is finite once fully melted, it can no longer absorb heat until it solidifies again at night.

Integrating windcatchers with materials of high thermal mass, night ventilation strategies, and other water features can further improve their effectiveness [141]. High thermal mass materials can absorb and store heat during the day, releasing it at night to maintain a stable indoor temperature. However, these materials can increase the structural load and construction costs. Night ventilation strategies, which involve cooling the building with cooler nighttime air, can be effective but require precise control mechanisms to avoid overcooling. Additionally, integrating windcatchers with other water features, such as fountains or water walls, can enhance cooling through evaporative effects [119]. But these systems also require a reliable water source, which can be challenging in arid regions.

The integration of these technologies with windcatchers requires careful consideration of local climate conditions, water availability, and construction costs. Further research and optimization are necessary to fully realize their potential and address the challenges associated with their implementation.

4.3. Group C: temperate climates

Temperate climates, characterized by moderate seasonal variations and mild weather conditions, present unique opportunities and challenges for the implementation of windcatcher technologies [26]. Since 2003, summer temperatures in the moderate European regions have notably increased [141]. Moreover, summers in temperate climates can vary significantly, ranging from cool (Edinburgh, Scotland) to warm (Melbourne, Australia) to extremely hot (Shanghai, China). These regions require ventilation solutions that provide not only heating but also cooling throughout the year, ensuring optimal indoor comfort and energy efficiency.

Providing indoor thermal comfort during warm summers in temperate climates can be achieved cost-effectively. Natural ventilation is particularly effective in reducing energy consumption from mechanical ventilation systems in these regions. For instance, in Denmark, where the high latitude means summer temperatures are not excessively high, natural ventilation can prevent building overheating. In a case study, natural ventilation was able to replace mechanical ventilation for 90 % of the operational time [142]. However, in scenarios where outdoor temperatures are hot and humid, similar to tropical climates, the cooling effect of natural ventilation is limited. This limitation also affects the performance of integrated passive or low-energy technologies, reducing their overall effectiveness in maintaining indoor comfort.

In temperate climates with hot and dry summers, many passive or low-energy technologies used in hot and arid regions remain effective for providing indoor thermal comfort. Although summers in temperate regions may not be as hot and dry as those in arid regions like Iran, strategies such as evaporative cooling would still be effective in places like Greece [143,144] and Spain [23,145] for maintaining indoor thermal comfort.

During hot and humid summers, conditions in temperate regions differ from those in tropical regions, making EAHE effective. The colder winters in temperate regions lower soil temperatures, allowing the low-

temperature thermal mass in the soil to be stored and used for pre-cooling supply air during summer. If the soil temperature is lower than the dew point temperature of the outdoor air, the EAHE system can also reduce the moisture content in the supply air, enhancing indoor comfort [62]. Thus, the EAHE system integrated with windcatchers is particularly effective in these regions due to lower soil temperatures in summer and higher soil temperatures in winter compared to outdoor temperatures.

Moreover, both summer and winter ventilation needs must be considered in temperate regions. In mild or cold winters, a high ventilation rate can cause thermal discomfort due to excessive heat loss. Passive designs for buildings in cold seasons mainly focus on minimizing heat loss and maximizing heat gains, such as capturing solar radiation. Preheating supply air in winter can also be provided by the EAHE system, as the soil temperature in winter is higher than the outdoor air temperature. This can substantially reduce the winter heating demand in a passive house with an EAHE system [62]. Therefore, integrating the EAHE system into a windcatcher can be a suitable solution for maintaining indoor thermal comfort in temperate regions.

An illustrative example of this challenge is found in Sweden, where most regions have temperate climates characterized by cold winters. Swedish houses are typically well-insulated and rarely equipped with air conditioning, similar to other regions in Europe. Consequently, the issue of overheating in summer is significant. Another potential solution is to integrate PCM within the windcatcher's inlet channel [97] and building fabric, which can effectively reduce overheating issues by absorbing excess heat during peak temperatures and releasing it during cooler periods, thus maintaining stable indoor conditions [146]. However, despite the clear potential of PCM for enhancing thermal comfort, research on PCM integration with windcatchers in temperate climates is limited. Given the distinct seasonal demands of temperate regions, the passive cooling potential of windcatchers with PCM needs further investigation, especially in well-insulated buildings or passive houses.

Combining a windcatcher system with a solar-heated wall has the potential to enhance indoor thermal comfort [24]. In winter, the solar-heated wall passively absorbs and stores solar energy during the day and gradually releases this heat indoors, effectively increasing indoor temperatures through gentle buoyancy-driven ventilation air circulation. In summer, the solar-heated wall facilitates buoyancy-driven ventilation by heating air near its interior surface, causing the warm air to rise and promoting natural airflow. However, integrating these two systems can be challenging, as windcatchers typically direct cool air downward, whereas solar-heated air naturally rises, potentially counteracting the intended airflow paths. Therefore, further research is needed to optimize the combined use of windcatchers and solar heated walls to utilize both systems effectively.

Heat recovery systems are commonly used in ventilation systems in cold regions. To apply heat recovery in windcatcher systems, techniques with low system pressure loss, such as heat pipes [86] and passive thermal wheels [88], have been proposed. However, adding heat recovery can be counterintuitive in summer, as it might inadvertently increase indoor temperatures when cooling is needed. This highlights the need for seasonal adjustments or mechanisms to ensure that heat recovery systems do not contribute to overheating during warmer months.

The studies listed in Table 5 demonstrate the potential for integrating various passive cooling and heating technologies with windcatchers in warm-summer temperate to Mediterranean settings. Evaporative cooling, and heat recovery systems have all shown promise in enhancing thermal comfort and reducing energy consumption. The key to their effectiveness lies in the careful consideration of local climatic conditions and the specific seasonal demands of the building, which necessitates a flexible and well-designed approach [147]. Further research should focus on optimizing these integrations and exploring new combinations to maximize energy efficiency and indoor comfort in temperate environments.

Table 5
Passive and low-energy technology integration with windcatcher in a temperate and warm temperate region.

Passive technology integration	Ref	Location/ weather data	Performance
Cooling			
Evaporative cooling	[50]	Madrid, Spain	6–8 °C temperature reduction
	[143]	Athens Greece	4 °C temperature reduction
	[144]	Greece	2 °C temperature reduction
	[148]	Cuernavaca city, Mexico	Predicted percentage of dissatisfied less than 10 %
	[145]	Seville, Spain	6 °C temperature reduction
Heating			
Coaxial heat exchanger	[84]	London, UK	Indoor temperatures fell within BB101 recommended limits for 90 % of all occupied hours
Heat pipe heat recovery	[86]	UK	4.5 °C temperature increasing
Thermal wheel heat recovery	[88]	UK	1–4 °C temperature increasing

As shown in Table 5, evaporative cooling systems remain suitable for summer cooling in regions with dry summers, utilizing water evaporation to lower air temperature and increase humidity. However, their effectiveness in humid climates is limited. Therefore, the suitability of evaporative cooling must be evaluated based on the specific climate conditions of the local conditions.

Heat recovery systems are essential in regions with prolonged cold winters, capturing heat from outgoing air to warm incoming air, reducing heating energy. Incorporating these systems into windcatchers requires careful consideration due to factors such as varying wind directions and potential airflow obstructions [149]. Multidirectional windcatchers [59], such as those with heat pipe heat recovery, have demonstrated effective integration of passive heat recovery [60]. A seasonal control system with a bypass mechanism can optimize performance, allowing the heat recovery unit to be bypassed during summer to prevent overheating, while maximizing energy savings in winter. This strategy is especially valuable in locations characterized by long heating seasons and relatively mild but increasingly warm summers, such as much of the UK.

Furthermore, incorporating glazed sections in windcatchers can help trap solar heat during colder days, warming the heat recovery components or directly preheating the incoming airflow [150]. This approach captures and retains solar energy, improving the efficiency of both ventilation and heating systems by preheating the incoming air [151, 152]. Applying a multidirectional windcatcher with a fixed airflow direction, maintaining consistent supply and exhaust channels irrespective of wind direction [59,60], offers a possible solution to ensure solar energy is consistently harnessed on the supply side of the ventilation system.

While these technologies offer benefits, they come with challenges such as high initial installation costs, complexity, and maintenance needs. For instance, EAHE systems require regular cleaning, evaporative cooling systems need a reliable water source, and heat recovery systems must be routinely maintained to ensure efficient heat exchange and avoid blockages or leaks. Additionally, local climatic conditions, building design, and occupant behaviors must be considered for optimal effectiveness.

4.4. Group D and E: continental and polar climates

Continental and polar climates present extreme conditions characterized by significant temperature variations. Continental climates experience warm to hot summers and severely cold winters, while polar climates endure long, harsh winters with short, cool summers. These conditions demand innovative approaches for integrating windcatchers

with passive technologies to achieve year-round thermal comfort and energy efficiency.

Research on windcatcher applications in continental and polar climates is currently absent, primarily due to the common avoidance of natural ventilation to prevent heat loss during cold periods. In continental regions, natural ventilation alone may not meet fresh-air targets for approximately 27–79 % of occupied winter periods, potentially compromising indoor air quality [153] and pushing buildings toward energy-intensive mechanical solutions. EAHEs are promising in continental climates because even in winter the ground is still warmer than the outdoor air. The resulting pre-heating of the supply air makes EAHEs a valuable companion to windcatchers, provided that frost-protection and condensate-drainage measures are included [62].

The substantial temperature differences between indoors and outdoors during winter significantly increase heating loads, emphasizing the importance of heat recovery strategies [154,155]. However, conventional heat-recovery technologies like heat pipes and rotary thermal wheels frequently underperform in extremely cold climates due to frost accumulation and increased pressure drop, resulting in diminished heat-transfer efficiency. This highlights the need to explore alternative or supplementary technologies for effectively integrating windcatchers in continental and polar environments.

Solar thermal systems and biomass-fueled stoves represent viable complementary heating solutions. Solar thermal systems capture and store solar energy to preheat incoming air [156], effectively reducing heating loads during sunny winter conditions, which makes them particularly beneficial in continental climates. Nevertheless, their applicability in polar regions is limited due to shorter daylight periods and lower solar intensity.

Biomass stove heating is widely used in regions such as Europe [157] and China [158] because of the affordability and renewable nature of fuels like wood [159] and straw [158], provided they are sustainably harvested [160]. Despite their efficiency and significant heating potential, direct stove heating introduces health risks associated with indoor pollutants such as PM_{2.5} [161] and carbon monoxide emissions [162]. Indirect stove heating, which separates combustion processes from indoor spaces, is safer but often costlier without government subsidies [163]. Additionally, substantial heat loss through flue gases necessitates effective waste heat recovery strategies, such as integrating mechanical ventilation systems specifically designed for stove heat recovery [164].

Combining multidirectional windcatchers, such as flap fin louvers [59] and rotary scoop windcatchers [60], with integrated solar thermal and biomass stove systems presents a promising approach for continental and polar climates. This integrated strategy recovers chimney heat from stoves to preheat supply air, maximizing biomass combustion efficiency, while solar thermal integration further reduces reliance on traditional heating methods during winter. However, such integrations increase complexity, cost, maintenance demands, and space requirements. Careful consideration of advanced design practices, robust safety measures, efficient heat distribution, and precise implementation is essential to successfully address the unique challenges posed by these climates.

4.5. Suitability of passive and low-energy technologies in windcatcher systems across climates

Fig. 8 groups the most promising integrations with windcatchers by climate. Some combinations, such as direct evaporative cooling in hot-arid zones or EAHE-plus-heat-recovery in temperate zones, are already backed by field data. Others remain largely at the proposal stage and still need real-world testing. In humid tropics, solar-powered indirect evaporative cooling paired with passive dehumidification offers a path to comfort without adding moisture. Hot-arid regions can rely on direct evaporative pads, EAHE tubes and PCM inserts, provided that water-saving strategies are in place. Temperate climates gain most from

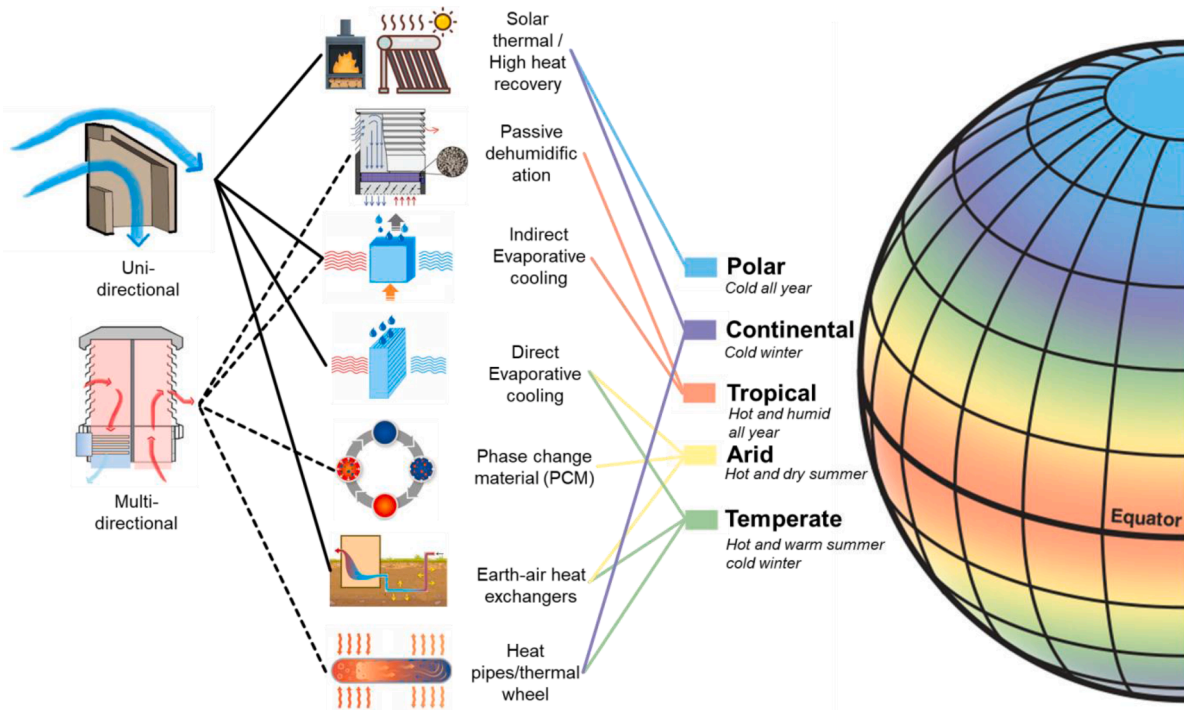


Fig. 8. Summary of suitable passive and low-energy technologies in windcatcher systems in different regions.

EAHE preconditioning, low-pressure heat-recovery and supplemental solar-thermal pre-heat.

For continental and polar settings, the options listed room-sealed biomass stoves whose flue heat is recovered in a multi-directional windcatcher, and, in continental but not polar latitudes, solar-thermal pre-heating, should be viewed as forward-looking concepts rather than proven solutions. These ideas still require pilot projects to confirm frost control, pressure-loss management and long-term reliability in extreme cold. In every climate, success hinges on thoughtful integration, local resource constraints (especially water), and a maintenance plan that keeps the passive systems performing as designed.

5. Challenges and future perspectives of windcatchers

5.1. Challenges of windcatchers in a changing climate and urban environments

The integration and optimization of windcatcher systems in modern buildings present various technical and practical challenges, particularly in the context of climate change and increasing urbanization. Addressing these barriers is critical for ensuring that windcatchers remain effective, efficient, and adaptable across diverse climate regions and building applications [56,165–167].

One significant challenge for windcatchers is dealing with the inherent variability of wind conditions [168,169]. Wind speed and direction fluctuate considerably, directly impacting the performance and consistency of natural ventilation systems [52,170]. Many traditional windcatcher designs do not adequately address variations in wind direction, resulting in suboptimal performance, particularly when integrated with passive or low-energy technologies [171]. For instance, integrating evaporative cooling with a solar chimney in a windcatcher system effectively provides cool air; however, this combination often functions efficiently only for specific wind directions. Any deviation from ideal wind direction can cause reverse airflow, resulting in thermal discomfort rather than effective cooling [172]. Similarly, cooling pipes integrated into the inlets of a two-sided windcatcher to cool the incoming air can experience reverse flow when the wind direction shifts,

leading to unnecessary energy losses [173]. Therefore, innovative design solutions that enhance directional adaptability are critical to maintaining consistent indoor comfort and air quality [68].

Another notable challenge involves maintaining thermal efficiency across extreme climatic conditions. Traditional windcatcher designs face significant difficulties in tropical regions, where high humidity and elevated temperatures can hinder effective passive cooling. Conversely, in temperate climates, incorporating heat recovery into windcatchers may unintentionally contribute to overheating during warmer periods, complicating the balance between heating and cooling demands. Overcoming these issues requires integrating advanced technologies such as EAHE, PCM, and solar thermal systems, which, while effective, also increase the complexity and cost of windcatcher systems.

Climate change further compounds these challenges, threatening both the performance and durability of windcatchers. Rising global temperatures, altered wind patterns, increased frequency of intense storms, and unpredictable precipitation can significantly affect natural ventilation performance. Moreover, prolonged exposure to harsh environmental conditions, dust accumulation, and general wear and tear can degrade system efficiency and lifespan. Regular maintenance, robust construction, and the use of durable materials become essential but add further cost implications. Despite the importance of durability, few existing studies focus comprehensively on maintenance strategies or long-term resilience, resulting in windcatcher installations that may not reach their intended performance or longevity. Hence, future research must emphasize designing windcatcher systems resilient enough to accommodate evolving climatic conditions while minimizing maintenance needs.

Additionally, emerging climate trends underscore the necessity for adaptive passive ventilation solutions. For instance, over the past four decades, summers in China have grown increasingly hot and humid, complicating indoor climate control [174]. Similarly, Canada anticipates experiencing hotter, wetter summers and milder winters [175]. In Central Africa, escalating temperatures and unpredictable rainfall patterns intensify living conditions for an expanding population [176]. Given these changing conditions, future windcatcher systems and passive technologies must be specifically developed and optimized to meet

the anticipated climatic shifts across diverse global regions.

Moreover, densely built urban environments present unique additional challenges for implementing windcatcher systems integrated with passive or low-energy technologies. High-rise buildings and urban structures significantly alter local wind patterns, reducing the effectiveness of natural ventilation and compromising adequate airflow. This disruption negatively impacts the cooling or heating performance of integrated passive solutions, posing barriers to effective implementation. Additionally, limited open spaces and overshadowing in urban areas often restrict the integration of solar devices, hindering solar thermal applications and other solar-dependent technologies. This necessitates alternative solutions or supplementary strategies for achieving energy-efficient performance in urban contexts.

Furthermore, many urban buildings feature high internal partition-wall densities, substantially impeding natural airflow pathways. Simplified ventilation models typically overlook these internal architectural obstructions, leading to uneven air distribution, where some rooms receive excessive airflow, while others become stagnant, compromising overall thermal comfort [177]. Consequently, future studies must consider detailed analyses of architectural layouts, examining precise positioning and design of windcatchers or side-catchers to optimize internal airflow and address localized ventilation needs [178]. Research should extend beyond basic airflow analysis to encompass thorough assessments of indoor air distribution following humidification or cooling processes, ensuring uniform and comfortable indoor climates throughout complex building layouts [59]. Critical related issues, such as moisture condensation, mould growth, and variations in thermal sensation across different spaces, must also be prioritized in future investigations.

Furthermore, effectively optimizing windcatcher performance under diverse climatic conditions and complex urban settings requires sophisticated control systems. These systems should dynamically regulate ventilation rates, precisely manage airflow patterns, and integrate supplementary heating or cooling technologies when necessary. Utilizing real-time data on indoor and outdoor temperatures, humidity levels, and fluctuating wind conditions will be essential for efficiently maintaining optimal indoor environments. The integration of artificial intelligence (AI)-enhanced control strategies, capable of predictive modeling and adaptive environmental responses [179], will further improve system performance, enhance resilience, and maximize energy efficiency in changing climates and increasingly complex urban landscapes.

Lastly, incorporating windcatchers into modern urban architecture poses aesthetic challenges not as common in rural or industrial areas [180]. For example, the geometry and height of windcatcher inlets significantly influence both visual appeal and ventilation efficiency [181], as taller, larger, or more complex structures may visually dominate or clash with the architectural style of urban buildings. Thus, balancing aesthetics with performance is crucial. Increasing the inlet area initially enhances airflow, but further expansion leads to diminishing returns due to airflow detachment and internal pressure constraints [43]. Further research should therefore explore aesthetically integrated windcatcher designs suitable for urban buildings with high fresh-air demands, such as multi-story systems combining windcatchers and solar chimneys [182–184].

5.2. Lacking standardized windcatcher designs for integrating natural ventilation and passive technology

Despite advancements in passive cooling [52,170,171] and heat recovery [83,85–87], the impact of varying wind directions on windcatcher performance is still insufficiently addressed in current research [168]. Traditional windcatcher designs often overlook sensitivity to wind direction changes, potentially causing performance inconsistencies, such as reverse airflow and thermal discomfort [60,87]. For instance, a UK case study demonstrated that a natural ventilation system integrating heat recovery effectively provided fresh air with low

energy use, yet its effectiveness notably fluctuated with changing wind directions [84]. Consequently, researchers frequently rely on controlled wind tunnel experiments to ensure stable results, highlighting a disconnect between controlled studies and practical applications.

A primary limitation of existing research is the lack of standardized windcatcher designs, complicating direct comparisons and hindering performance evaluations of passive or low-energy cooling and heating technologies. Studies typically involve numerous variables, such as wind speed, wind direction, temperature, and windcatcher geometry, that make isolated analysis challenging. Establishing standardized multidirectional windcatchers would streamline research by reducing variables such as size and directional sensitivity, allowing wind speed and temperature to emerge as primary comparative factors.

Standardizing windcatcher designs would offer substantial benefits in both practical and research contexts. It would enhance consistency and predictability of natural ventilation performance, simplify system scaling, and facilitate optimization across diverse building types and climates. Additionally, standardized designs would promote best practices, improve reproducibility of research outcomes, and encourage innovation by enabling clear comparative assessments of various passive ventilation technologies. Moreover, conducting field studies under realistic wind conditions is crucial for validating the performance of standardized multidirectional windcatchers when integrated with passive heating and cooling technologies [57,184].

6. Conclusion

This comprehensive review of 147 studies has explored the advancements, challenges, and future perspectives of integrating windcatcher systems with passive and low-energy technologies across various climates. The distribution of studies covers different windcatcher types, methodologies, and their application in ventilation, heating, cooling, and dehumidification technologies.

Windcatcher designs varied, with single-sided windcatchers being the most researched, followed by two-sided and four-sided configurations. Most studies focused on CFD simulations, often combined with experimental testing, while field studies, though less common, were crucial for validating simulation results and understanding real-world applications. Research primarily targeted natural ventilation and passive or low-energy cooling, with significant attention to regions like the Middle East, temperate areas in Europe, and tropical climates such as Malaysia.

In **hot and arid climates**, evaporative cooling proved highly effective, achieving temperature reductions of over 10 °C in regions like Yazd City, Iran, and Masdar City, Abu Dhabi. However, water scarcity is a significant issue for evaporative cooling systems in arid regions, limiting their sustainability and effectiveness. Integrating EAHE with windcatchers showed promising results, offering cooling capacities of up to 30 kW and temperature reductions of up to 20 °C in Ouargla, Algeria.

In **temperate climates**, balancing cooling in summer and heating in winter presents unique challenges. The EAHE system effectively utilizes soil temperatures to provide pre-cooling in summer and pre-heating in winter. Heat recovery systems, such as heat pipes and thermal wheels, can enhance energy efficiency, though they must be carefully managed to avoid overheating. Studies in the UK and other temperate regions showed indoor temperature improvements ranging from 1 °C to 4.5 °C. Combining windcatchers with solar thermal heating and PCM can further optimize thermal comfort and energy efficiency, despite the increased complexity and cost. The effectiveness of PCM is also constrained by the substantial amount required to maintain consistent cooling over longer periods.

In **tropical climates**, high humidity and variable wind conditions complicate traditional windcatcher designs. Indirect evaporative cooling, which separates cooling and humidification processes, emerges as a viable solution to maintain indoor humidity at acceptable levels. Future research should focus on developing designs that integrate indirect

evaporative cooling with windcatchers, potentially powered by solar energy.

For **continental and polar regions**, extreme cold and variable climatic conditions require robust solutions. Traditional heat recovery units may be less effective, but integrating windcatchers with stoves and advanced heat recovery systems offers a viable alternative. Multidirectional windcatchers, combined with heat recovery units and stoves, can maximize heating efficiency and ensure a consistent fresh air supply, though addressing increased complexity, cost, and maintenance is crucial.

Addressing the identified challenges can make windcatchers vital for reducing energy consumption, improving indoor air quality, and promoting sustainable development. This review provides a foundation for future studies to maximize windcatcher potential in diverse climates.

CRediT authorship contribution statement

Jiuxiang Li: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **John Calautit:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Conceptualization. **Carlos Jimenez-Bescos:** Supervision, Conceptualization. **Wenjie Song:** Writing – original draft. **Saffa Riffat:** Supervision. **Qun Chen:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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