The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter

Asma Khalid, Nur Dalilah Dahlan, Mohd Firdaus Bin Abas, Kamarul Arifin Bin Ahmad and Mohd Fairuz Shahidan

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

The Impact of Wind Catchers on Thermal Comfort and Indoor Air Quality, an analysis of Subtropical climate for summer and winter

Authors' Names

The list of authors and their affiliations are as follows:

1. Asma Khalid (**corresponding author**) [asma.khalid@uet.edu.pk]
   [a]Department of Architecture,
   Faculty of Design and Architecture,
   Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.
   [b]Department of Product and Industrial Design
   University of Engineering and Technology, Lahore, Pakistan
2. Nur Dalilah Dahlan
   Department of Architecture,
   Faculty of Design and Architecture,
   Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.
3. Mohd Firdaus Bin Abas
   Department of Mechanical Technology,
   Faculty of Mechanical & Manufacturing Engineering,
   Universiti Tun Hussein Onn Malaysia
4. Kamarul Arifin Bin Ahmad
   Department of Aerospace Engineering,
   Faculty of Engineering,
   Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.
5. Mohd Fairuz Shahidan
   Department of Landscape,
   Faculty of Design and Architecture,
   Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.

Key Words

Wind Chimney, Wind Catcher, Thermal Comfort, Indoor Air Quality, Sub-tropical Climate, Standards

Abstract

Employees spend 8 hours of the day with a minimum of 40 hours a week in offices. The office design, furniture and ventilation modes cause high energy consumption, pollutants and sick building syndrome amongst employees. Based on ASHRAE standards and WHO ~~standards~~ guidelines, the study evaluated offices for the temperature, humidity, $PM_{2.5}$, CO_2 and employees' subjective assessment. The offices met humidity standards except for the Punjab Civil Secretariat (PCS) (61.9%, ±0.1) and the Directorate of Public Instruction (54.1%, ±0.3) in the summer and winter respectively. The concentrations of CO_2 in offices were unhealthy for both seasons except the PCS (697.3 ppm, ±9.2) and Punjab Skill Development Authority (838.9 ppm, ±13.3). The mean $PM_{2.5}$ concentration for offices was unhealthy

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

during summer (28.4-53.7μg/m^3) and hazardous in winter (178-233.7 μg/m^3). The one-way ANOVA of employees' subjective assessment showed that the results were significant ($p < 0.05$) for indoor air quality, thermal comfort satisfaction, preference, health effect, filtration and wind catcher preference, for two seasons and within ventilation modes. The familiarity with wind catcher designs was insignificant ($p > 0.05$) but employees preferred their modern applications. The comfort indexes showed that the Governor House (PMV-0.04, PPD 5%) met the thermal comfort standards during winter.

Introduction

Pollution in the cities of Pakistan, [1] and Particulate Matter ($PM_{2.5}$) concentrations in Lahore have critically surpassed [2–4] the World Health Organization (WHO) guidelines. [5] Rapid urbanization, unprecedented construction, emissions from raw material production, brick kilns, other industries and vehicle exhausts contribute to pollutants in the urban atmosphere. [6] Pollution research was expedited after the schools' closure and offices shifted remotely in Lahore. [7] According to the Strategic Country Environmental Assessment (SCEA), [8] environmental degradation burdens about 6% of Pakistan's economy to the cost of urban [Rs.65 billion per year (b/y)] and indoor pollution [Rs 67b/y]. [9] People spend 90% of their time indoors and come across pollutants from heating, cooling, lack of ventilation [10] and daily activities due to the exchange of heat energy from the human body. [11] Higher $PM_{2.5}$ concentration, increased occupants, space heating, cooking, cleaning, indoor smoke, outdoor smog, vicinities close to semi-industrial locations and high traffic loads were the major sources of pollutants [12] compromising the ambient air quality and not meeting the WHO guidelines. [5] Long-term exposure to pollutants has serious implications in millions of new diabetes cases each year. [13] Pakistan can increase life expectancy [14] by following the interim WHO $PM_{2.5}$ guidelines of a 24-hour mean concentration of 15 µg/m. Employees' performance and motivation for healthy indoor office environments depend on thermal comfort and Indoor Air Quality (IAQ). [15] Studies proved that poor IAQ could significantly impact physiological health, psychological tasking and work-related cognitive performances.[16–18] Increased indoor pollutants and sick building syndrome could affect employees' physical and mental health. [19] The ventilation in offices of Pakistan is done with various controls like fans, coolers, split air-conditioned, Heating Ventilation and Air Conditioning (HVAC) systems [20] and passive measures of building form, orientation, [21] window cross ventilation and courtyard, etc. The air-conditioned buildings are mechanically ventilated, consume high energy and release Green House Gas (GHG) emissions. [22] Occupants could experience discomfort due to thermal shifts in air-conditioned and non-air-conditioned environments. Passive controls are used to achieve adaptive comfort, [23] energy efficiency and by monitoring the effect of IAQ and thermal comfort. [24] The office windows could lead to noise pollution in the indoor built environment. Zahid [25] and Colbeck [6] reported that employees faced ventilation issues and $PM_{2.5}$ enriched indoor environments due to non-compliance with the WHO guidelines. [5]

Murtyas [22] has shown that passive cooling methods would potentially be applicable till 2050 to achieve sustainability. The wind catcher would improve thermal comfort and IAQ through frequent air exchange and reducing indoor CO_2 concentration. [26] The old wind chimney has been utilized in both seasons for thermal comfort [27,28] with bricks used as thermal mass and a narrow metal seize at the junction of the channel and column, which is used to filter and function as the fireplace during winter. The new wind catchers are small portable, modular, factory-manufactured, site-transported and passive cooling devices with dampers and louver control to achieve thermal comfort and IAQ. [29–31] The recent innovation in wind catcher designs to use natural ventilation potential with solar chimney integration has been numerically and experimentally demonstrated for space cooling. [27,32,33] The research is novel in applying the empirical method of post-occupancy evaluation with and without a wind chimney in Lahore's offices. The study aimed to measure the impact of wind catchers on thermal comfort and IAQ in the Lahore offices with/without wind chimneys and compared the environmental parameters of temperature, humidity, CO_2 and $PM_{2.5}$ concentrations with ASHRAE 55 [34], adaptive comfort reference [35], CIBSE Guide, [36] US EPA regulations [37] and WHO [5] guidelines during summer and winter. The

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

subjective assessment of IAQ, thermal comfort, physiological and psychological health symptoms, existing filtration choices and wind catcher perception was measured in offices in Lahore.

Methodology

The research followed the process (Figure 1) of selecting wind chimney offices and measured the comfort performance according to ASHRAE 55 standard [34], adaptive comfort reference [35], CIBSE Guide [36], EPA Regulations [37] and WHO Guidelines. [5] The survey protocol received approval from the Ethics Board of Approval of Universiti Putra Malaysia (GP-IPS/2022/973690).

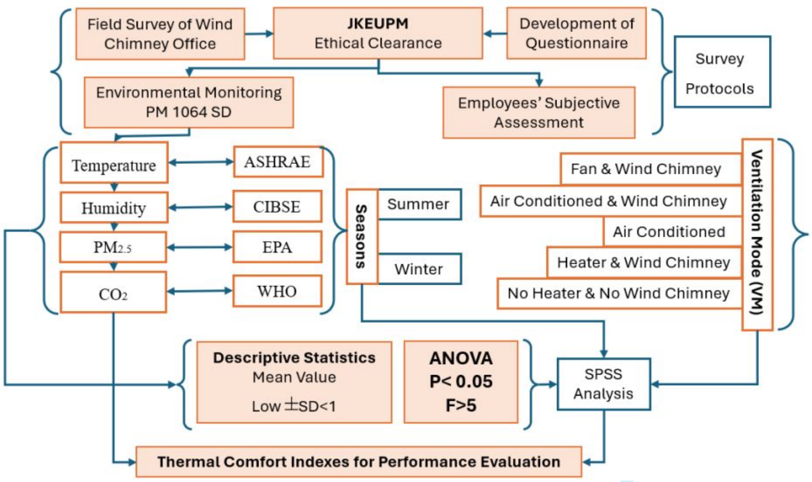


Figure 1 Flow chart of Research Process

In two separate field measurements during summer and winter, a purposive sampling method was chosen, with an equal sample size of 196 from four offices, with 49 respondents from each office. In the subjective survey, employees were asked about their demographics, thermal and IAQ satisfaction and preference, health symptoms, filtration choices, wind catcher familiarity and preference. The data collected from the field survey was used to access the thermal comfort indexes and performance evaluation of measured offices.

Sub-tropical Climate of Lahore

Lahore is located at 31°32′59″N of Latitude and 74°20′37″E of Longitude (216 above the sea level), categorized as a humid subtropical climate (BSh) according to the Köppen climate classification [38] with characteristics for long durations of extreme summer and mild winter. Figures 2 - 5 provide the climate summary of Lahore, based on the data analysed for the years 2009 - 2023. [39] The average yearly temperature is 24.5°C, with the hottest annual temperature (99%): 42.5°C, the coldest yearly temperature (1%): 5.7°C, highest humidity in summer, 90%, lowest humidity in winter, 60% (Figure 2).

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

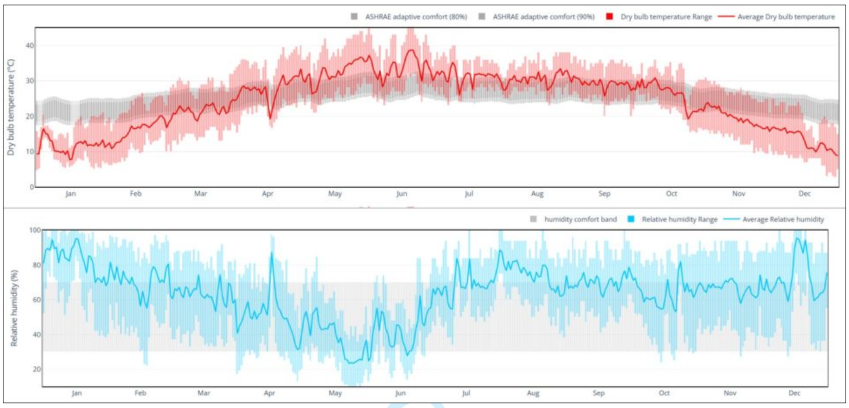


Figure 2 Dry Bulb Temperature (above) and Relative Humidity (below) for the Climate of Lahore, Pakistan [39].

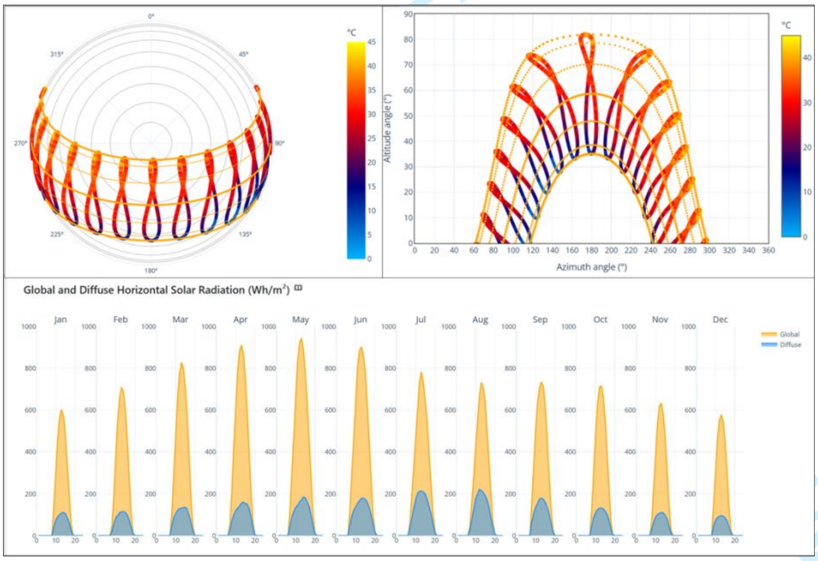


Figure 3 Sun Path Chart (above) and Global and Diffuse Solar Radiations (Wh/m²) (below) for Lahore, Pakistan [39].

The rotational angle of the sun is from East to West, with a summer solar altitude 80.06° and azimuth 180.35°. The monthly average hourly horizontal global solar radiations are 944 kWh/m² in May and 578 kWh/m² in December. The monthly average hourly diffuse solar radiations are between 93-213 kWh/m² (Figure 3). Lahore average maximum wind speed is between 0.5 – 10.7 km/h and the highest direction towards Northwest and Southeast (Figure 5).

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

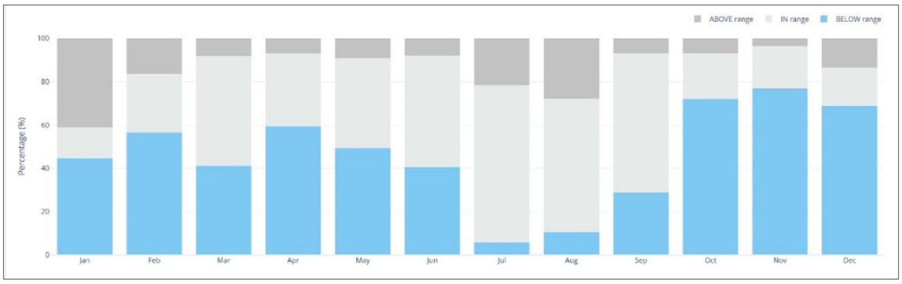


Figure 4 Cloud Cover for Lahore, Pakistan [39].

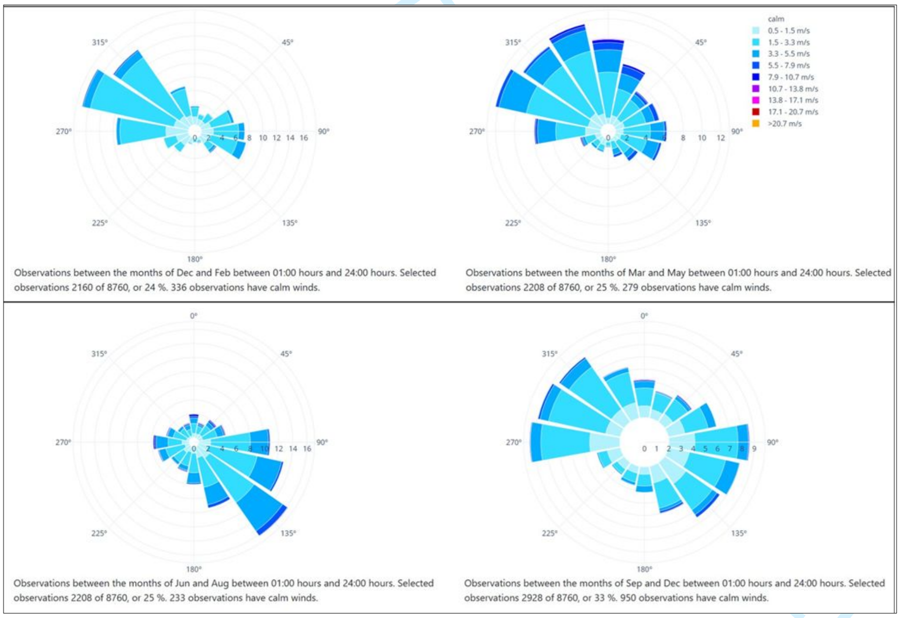


Figure 5 Seasonal Wind Rose [Dec-Feb, Mar-May, Jun-Aug, Sep-Dec] for Lahore, Pakistan [39].

Description of Cases

The criteria for selected offices were ventilation modes of splits air-conditioned with outdoor units, and fan-forced naturally ventilated wind chimney offices from the old colonial construction. The analysis of 4 office buildings, 3 having wind chimneys [Directorate of Public Instruction (DPI), Punjab Civil Secretariat (PCS), Governor House (GH)] and Punjab Skill Development Authority (PSDA), representing a modern office as the focus of the investigation *(Table 1)*. During summer, DPI and PCS have wind chimneys and fan-forced ventilation and PSDA, GH have wind chimneys and air conditioning as ventilation mode. During winter, DPI, PCS and GH use electric or gas heaters but PSDA does not use heaters during the measurement. All four offices are at different locations, so the level of indoor pollution varied according to the outdoor pollution. The offices of the DPI *(Figure 6)* and PCS *(Figure 7)* and the GH *(Figure*

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

8) and PSDA *(Figure 9)* were the selected locations in Lahore shown on the Google map *(Figure 10)*.

Table 1 Mapping of selected Cases with the Mode of Ventilation

No	Name of Office	Building Coordinates	Room Volume (m^3)	Ventilation Mode (VM)		
				Summer	Winter	Passive Method
1	Directorate of Public Instruction (DPI)	31.57, 74.31	3900	Fans	Gas Heater	WC
2	Punjab Civil Secretariat (PCS)	31.57, 74.30	6500	Fans	Gas Heater	WC
3	Governor House (GH)	31.55, 74.34	1320	AC	Gas & Electric Heater	WC
4	Punjab Skill Development Authority (PSDA)	31.50, 74.31	3000	AC	N.A.	N.A.

Note: *AC- Air Conditioned, N.A.-Not Applicable, WC-Wind Chimney*

Figure 6 Directorate of Public Instruction (DPI) (a) Outdoor vegetation, (b) Blocked veranda of DPI, minimizing cross-ventilation, (c) Exterior View of Wind Chimney, d) Interior View of Office, e) Wind Chimney Inlet/outlet, f) Wind Chimney used for shelf, g) Wind Chimney from inside of office

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

Figure 7 Punjab Civil Secretariat (PCS) a) Indoor Monitoring of PCS, b) Wind Chimney Office of Measured Office

Figure 8 Governor House (GH), a) Pothos Planter, b) Yucca Planter, c) Tabletop Aleo Vera Plant, d) Exterior Facade of Governor House (GH), e) Measured Office of GH, f) GH Wind Chimney from the interior

Figure 9 Punjab Skill Development Authority (PSDA) a) Measured Office, b) PM1064SD placed on the Office Table

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

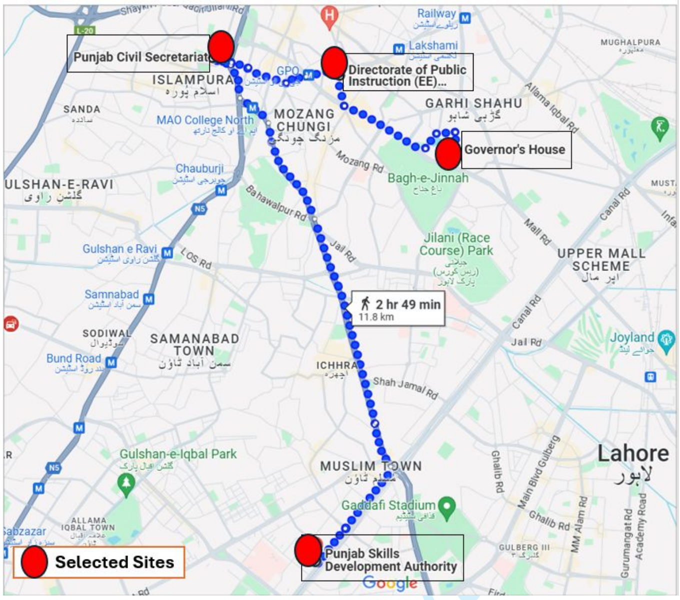


Figure 10 Locations of selected sites on Google Map

Sample selection and Subjective assessment

The cross-sectional survey protocol consisted of environmental monitoring and the subjective evaluation of IAQ and thermal comfort during summer and winter. An ISO-9001 certified air quality monitor and recorder PM-1064SD *(Table 2)* was installed in four (4) offices of Lahore for real-time indoor monitoring of temperature, humidity and concentrations of $PM_{2.5}$ and CO_2. The device was placed on an office table for data collection with the data logged at every 1-minute interval following ASHRAE's Handbook of Fundamentals. [34]

Table 2 Details of the PM 1064 SD

No	Measuring Parameter	Accuracy	Range	Resolution
1	Temperature	± 0.8°C	0-50°C	0.1°C
2	Humidity	< 70%RH: ± 3%RH	5-95%RH	0.1% R.H.
3	CO_2	± 40 ppm, ≦ 1000 ppm	10,000 ppm	1 ppm
		± (50 ppm + 3% of reading) > 1,000 ppm ≦ 3000 ppm		
		± (50 ppm + 5% of reading) > 3,000 ppm ≦ 10000 ppm		
		Repeatability: ± 20 ppm > 3,000 ppm ≦ 10,000 ppm		
4	$PM_{2.5}$	± (10% reading ± 15 µ g/m³)	0-250 µ g/m³	1 µ g/m³
5	Pressure	± 1.5 hPa ± 2 hPa	10.0 to 999.9 1000 to 1100	0.1 hPa 1 hPa
6	Health Index		0-9	
7	Sampling Time		2-3600 Seconds	

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

The approved questionnaire consisted of six (6) sections, gathering respondents' queries about IAQ, thermal comfort, filtration choices, wind catcher familiarity and preferences. The indoor environmental quality survey [40] was adapted for thermal comfort [41–45] and IAQ [46–49] questionnaire with 3, 5 and 7-point scale ratings. The responses were gathered based on the ASHRAE 7-point bi-polar scale for thermal sensation, airflow, comfortable feel, IAQ acceptance, preferences and wind catcher perception with six pictorial stimuli for thermal comfort questions.

Data analyses

To standardize the environmental conditions, it is a regional practice to design, adapt and modify standards developed by the WHO Guidelines [5], ASHRAE 55-2023 Standard [34] and US EPA Regulations. [37] The Energy Conservation Building Code (ECBC) of Pakistan, [50] was adapted from standard practices and benchmarked values for HVAC, fan-forced and naturally ventilated buildings. The study compared summer and winter field measurements in four offices with the WHO Guidelines [5] and ASHRAE 55-2023 Standard. [34] Descriptive statistics and one-way ANOVA were used to compare the mean difference between 'summer and winter' and within the ventilation modes for four offices in Lahore. The significance level ($p < 0.05$) and the difference in groups were measured with the F-value >5 for the IAQ, thermal comfort and wind catcher. The performance of the wind chimney office was measured for IAQ satisfaction, IAQ preference, thermal comfort satisfaction, health symptoms, filtration methods, wind catcher familiarity and preferences. The employees' satisfaction in sampled offices was scored for performance between seasons and within ventilation modes. The IAQ and thermal satisfaction were further evaluated based on the ASHRAE 55 [34] and ISO 7730, [51] which requires 80-90% of people to be satisfied in the thermal environment. The survey results showed that the performance of wind chimney offices did not satisfy employees, but modern wind catchers were a preferred solution to achieve comfort in offices.

Results and Discussion

Table 3 showed the mean and standard deviation (±SD) of temperature and humidity measured in 4 offices for both summer and winter and compared it with the ASHRAE 55 standard [34] and adaptive comfort reference [35]. Considering adaptive comfort [35] helps to determine the flexible range of adapting people for comfort conditions, with various controls.

Table 3 Mean value of field measurement for Temperature and Humidity

Seasons	Building	Mean Temperature (°C)	SD ±	Building	Mean Humidity (%)	SD ±
Summer	s-DPI	33.4	0.1	s-DPI	54.1	0.3
	s-PCS	30.9	0.1	s-PCS	61.9	0.1
	s-GH	24.9	0.1	s-GH	60.1	0.5
	s-PSDA	23.4	0.1	s-PSDA	39.8	0.3
Winter	w-DPI	17.0	0.1	w-DPI	74.4	0.1
	w- PCS	13.6	0.3	w- PCS	46.5	0.4
	w-GH	15.8	0.2	w-GH	57.3	0.7
	w-PSDA	17.4	0.2	w-PSDA	66.0	0.3

Note: s-GH [Summer data-Governor House], w-GH [Winter data-Governor House]

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

s-DPI [Summer data-Directorate of Public Instruction], w-DPI [Winter data-Directorate of Public Instruction]
s-PCS [Summer data-Punjab Civil Secretariat], w-PCS [Winter data-Punjab Civil Secretariat]
s-PSDA [Summer data-Punjab Skill Development Authority], w-PSDA [Winter data-Punjab Skill Development Authority]

The study benchmarked the summer temperature standards of 23 - 26°C for air-conditioned offices, 23 - 30°C for adaptive comfort of fan-forced naturally ventilated offices, [35] 23 - 26°C based on ISO 7730 standard, [51] 20 - 27°C based on ASHRAE 62.1 standard [52] and 22 - 26°C based on the Energy Conservation Building Code (ECBC), Pakistan. [50] The comfort range for both temperature and humidity was plotted to determine whether fans forced naturally ventilated and air-conditioned offices complied or did not comply with the ASHRAE 55-2023 [34], and adaptive comfort reference [35] for the 8 hours of office. Notably, only the summer temperature of the air-conditioned offices in Lahore best complied with the existing ECBC, Pakistan. [50]

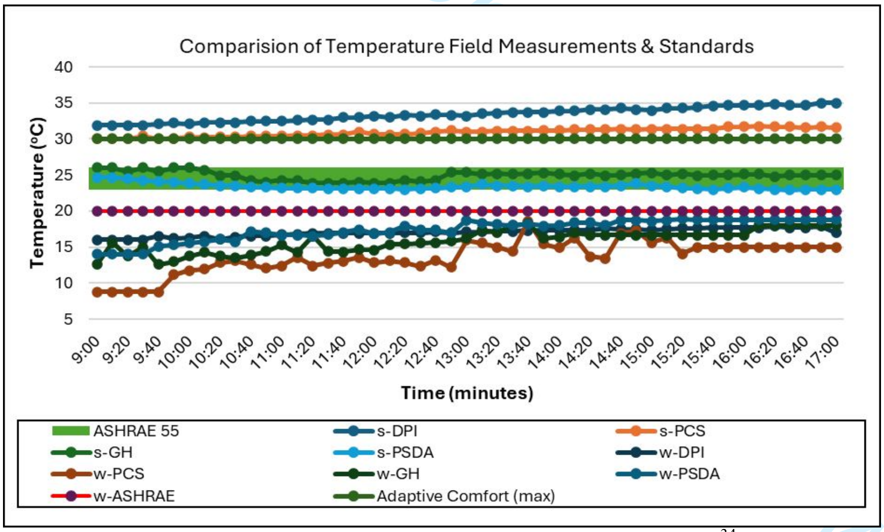


Figure 11 Comparing the Temperature of Sampled Offices with ASHRAE 55 standard [34], adaptive comfort reference [35], during Summer and Winter

Figure 11 compared the field measurements from wind chimneys and air-conditioned offices. During summer, the indoor temperature of air-conditioned offices [s-GH and s-PSDA] were within the comfort range of the ASHRAE 55 [34] (23 - 26°C) and adaptive comfort reference [35] (30°C) in wind chimney offices. In the s-DPI, the temperature was above the comfort standard throughout the summer day and people managed with various controls and adaptations. However, in the s-PCS, the comfortable indoor temperature from morning to noon rose gradually till the end of the day. In winter, the ASHRAE 55, [34] benchmarked indoor design temperature of 24°C, ISO 7730 [52] (20 - 24°C) and CIBSE [36] (19 - 23°C) standards were achieved. The study evaluated the winter comfort temperature (19 - 24 °C) below the measurements and found that the heater did not help to achieve comfort in offices. Most of the time, the doors were closed in all offices, and gas or electric heaters were common modes for

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

comfort in w-DPI and w-GH. In w-GH, there was no direct heating, but adjacent rooms had gas and electric heaters. The high ceiling (25'-0"), open office plan, and low height partitions in w-PCS have led to low temperatures compared to the other three measured offices, even in the presence of heaters.

The assessment of humidity was based on ASHRAE 55 Standard [34] (30-60%), adaptive comfort reference [35] (55-70%) and CIBSE Guide (40-70%) [36] *(Figure 12)*. According to ASHRAE 55 Standard [34], the air-conditioned and wind chimney offices [s-PSDA, s-DPI, s-GH, w-PCS, w-GH] met requirements of 30-60%. The s-PCS during summer and w-PSDA in winter did not meet the ASHRAE 55 requirements but fulfilled the CIBSE requirement of 70% humidity. In the w-GH office, indoor plants produced transpiration and increased the humidity. The humidity in early office hours till noon was within the comfort range and gradually increased in the afternoon. The office has infiltration because the door is constantly open for public and administrative dealings and the w-DPI was above the ASHRAE 55 Standard (30-60%) [34], adaptive comfort reference (55-70%) [35] and CIBSE Guide (40-70%) [36]. However, the same office was within the comfort range during summer due to the stack ventilation of wind chimneys and ventilators.

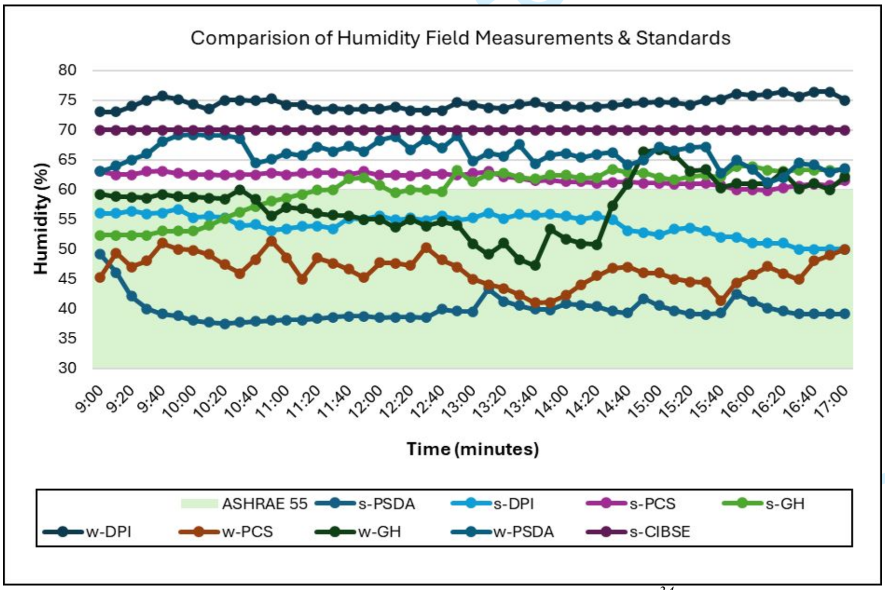


Figure 12 Comparing the Humidity of Sampled Offices with ASHRAE 55 Standard [34], adaptive comfort reference [35], during Summer and Winter

Figure 13 compared $PM_{2.5}$ concentrations during winter and summer and benchmarked the WHO guidelines of 15 μg/m³ for 24 hours on average [5] and no office met the criteria. However, USA-EPA [37] produced six categorizations that classify $PM_{2.5}$ concentration '0-50 μg/m³' as 'Good', '51-100' as 'Moderate', 'Unhealthy for Sensitive Groups' for '101-150', 'Unhealthy' for '151-200 μg/m³', '201-300 μg/m³' as 'very unhealthy' and '301+ μg/m³' as 'hazardous'.

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

Table 4 Mean concentrations of field measurement of $PM_{2.5}$ and CO_2

Seasons	Building	Mean $PM_{2.5}$ (µg/m ^{3})	SD ±	Building	Mean CO_2 (ppm)	SD ±
Summer	s-DPI	41.6	1.2	s-DPI	3536.9	16.6
	s-PCS	53.7	1.0	s-PCS	3944.6	10.2
	s-GH	50.0	0.6	s-GH	4203.5	14.3
	s-PSDA	28.4	0.5	s-PSDA	4037.0	10.2
Winter	w-DPI	233.7	3.4	w-DPI	1942.2	46.5
	w-PCS	178.0	2.7	w-PCS	697.3	9.2
	w-GH	198.9	4.2	w-GH	1828.1	63.5
	w-PSDA	200.6	3.9	w-PSDA	838.9	13.3

Note: s-GH [Summer data-Governor House], w-DPI [Winter data-Governor House]
s-DPI [Summer data-Directorate of Public Instruction], w-DPI [Winter data-Directorate of Public Instruction]
s-PCS [Summer data-Punjab Civil Secretariat], w-DPI [Winter data-Punjab Civil Secretariat]
s-PSDA [Summer data-Punjab Skill Development Authority], w-DPI [Winter data-Punjab Skill Development Authority]

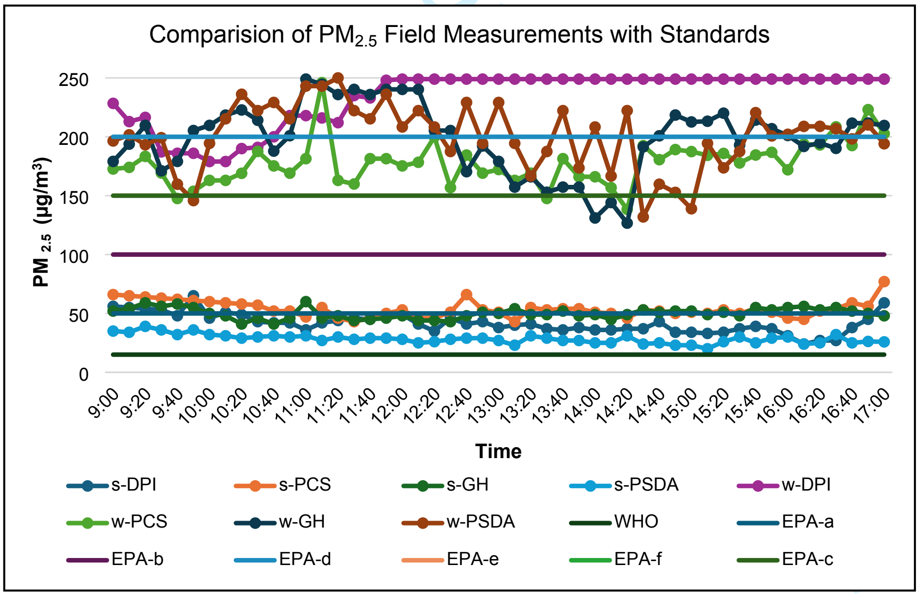
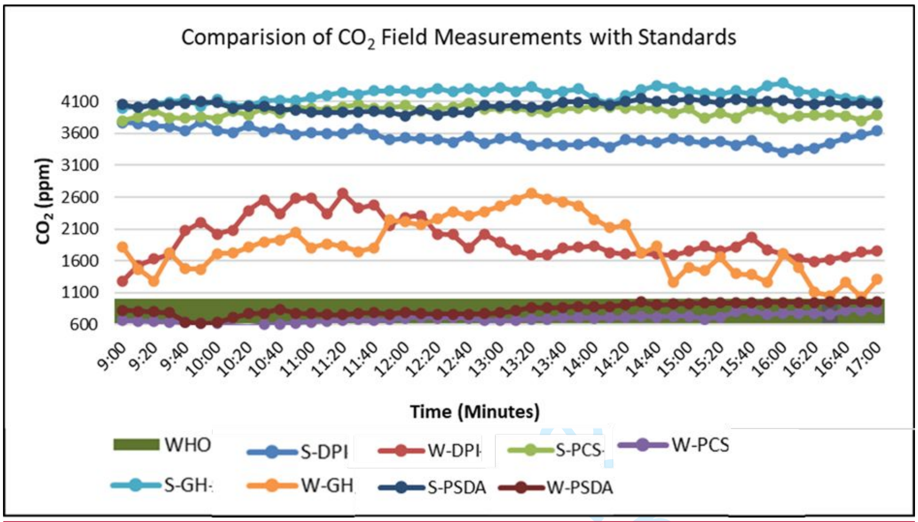


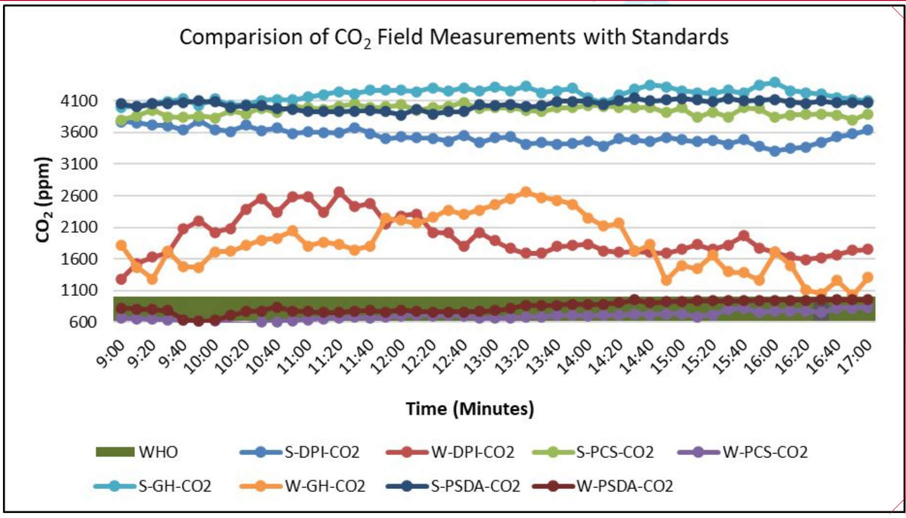
Figure 13 Comparing $PM_{2.5}$ concentrations in Sampled Offices with limit values given by ~~according to~~ WHO Guidelines~~,~~ [5] and USA-EPA Regulations [37] during Summer and Winter

The air-conditioned and wind chimney offices experienced less $PM_{2.5}$ concentration during summer than in winter *(Figure 13).* The s-PSDA has the lowest $PM_{2.5}$ concentration and was within the US EPA moderate region below 35.4 µg/m^3 as most indoor air was cleaned and recirculated from a split air-conditioner filter. The three offices s-GH, s-DPI and s-PAD were between 35.4 - 55.4 µg/m^3 and were considered unhealthy for sensitive groups with cardiovascular and respiratory illnesses. According to the WHO's recent guidelines, [5] the high $PM_{2.5}$ concentration could cause long- and short-term diseases including cardiovascular and respiratory illness for office workers in Lahore. During winters, the offices of PCS, GH and PSDA were in the range of 55.4 - 125.4 µg/m^3, suggesting an unhealthy risk for employees,

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

and DPI has a hazardous level of $PM_{2.5}$, exceeding greater than 250.5 μg/m^3 throughout the day. People should wear masks indoors, in winter and summer as dusty wind blows through the buildings, which is visible on office furniture.





Commented [CY2]: Subscript 2 in CO_2

Figure 14 Comparing CO_2 concentrations in Sampled Offices with ASHRAE 62.1 Standard (600-700 ppm), [5] *US EPA Regulations (800 ppm)* [53] *and WHO Guidelines (<1000 ppm)* [5] *during Summer and Winter*

The field measurements in wind chimneys and air-conditioned offices during summer and winter were compared with the ASHRAE 62.1 Standard (600-700 ppm), [5] US EPA Regulations (800 ppm) [37] and WHO Guidelines (<1000 ppm) [5] *(Figure 14)*. During winter, the w-PCS and w-PSD offices complied with the 1000 ppm standards throughout the day, but w-GH and w-

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

DPI showed greater fluctuation in CO_2 concentration far above the standards. The situation of all four offices was worse during summer in air-conditioned and wind-chimney offices due to the breathing effect of employees' decaying CO_2 concentration. [5] Wind-chimney offices have higher CO_2 concentrations during summer in air-conditioned offices.

Subjective assessment

The subjective assessment of respondents' data was statistically analysed for both summer and winter using IBM SPSS Statistics 26. The data described the demographic of employees from the sampled offices in Lahore. The employees are mostly males with an educational background of M.Phil./Master's degree and work for 6-8 hours. This suggests a highly educated workforce, with a strong emphasis on advanced education and a standard full-time work schedule within the measured offices *(Figure 15)*.

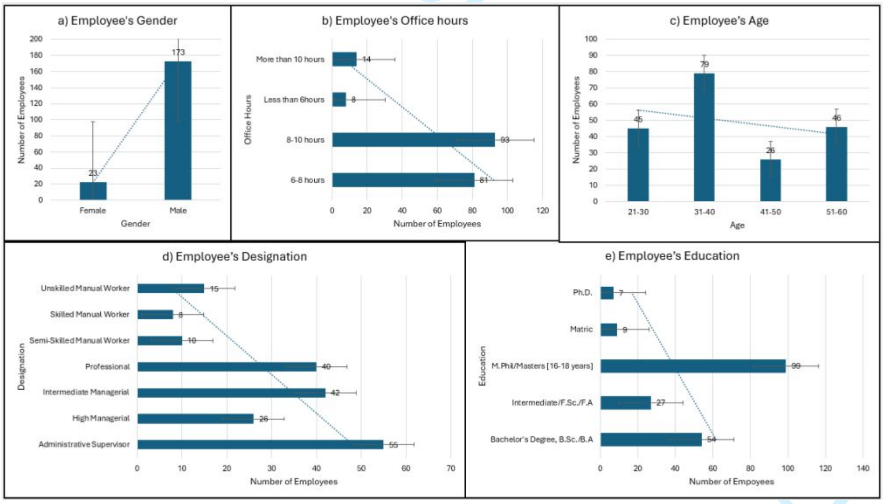


Figure 3 Demographics of Sampled Office Employees a) Employee's Gender, b) Employee's Office Hours, c) Employee's Age, d) Employee's Designation, e) Employee's Education

The office employees work full-time, and the age range of 31 - 40 is the most common, followed by 21 - 30, 41 - 50, 51 - 60 and above 60 years, representing a mix of early and mid-career professionals. Males hold an M.Phil./ master's degree and work 6-8 hours, suggesting a strong correlation between advanced education and management or supervisory roles. Conversely, females typically work 6-8 hours. The administrative supervisors and professionals are in the 31 - 40 years of a mid-career stage. Skilled and semi-skilled workers are common in other age ranges, indicating diverse roles and experiences. Further, the study quantified the subjective assessment of people's satisfaction and preferences with various factors. The five ventilation modes were 'Fan and Wind Chimney', 'Air Conditioned and Wind Chimney', 'Air Conditioned' during the summer, and 'Heater and Wind Chimney' and 'No Heater and No Wind Chimney' in winter.

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

Indoor Air Quality Satisfaction

Indoor air quality (IAQ) satisfaction was quantified by measuring the IAQ index, air quality parameters, the effect of IAQ on physical and mental health, the office's role in enhancing work conditions and satisfaction with the indoor environment (*Table 5)*. The results of ANOVA showed that the p-value was significant (p <0.05) for the 'air feel (F 26.8)', 'air quality problems (F 16.8)' and 'people being worried about air quality (F 14.0)' of the office during summer and winter. The employees' dissatisfaction with the air feel was slightly stuffy [4.7 (±1.36)] in summer and neutral [3.9 (±1.6)] in winter. In offices, the employees face the air problem of chemical odour [3.0 (±1.55)] in summer and 'visible mould and bad odour' [2.4 (±1.4)] in winter. The mean satisfaction vote [1.4(±0.59)] of people worried about the IAQ was higher in the summer than in winter [1.2(±0.51)]. However, physical and mental health, job performance and satisfaction with indoor conditions for office tasks and meetings were insignificant (p >0.05) in the two seasons.

Table 5 Descriptive Statistics and ANOVA Result of IAQ Satisfaction

Var	Seasons	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*	Ventilation Mode	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*
Worried	Summer	1.4	0.59			Fan & WC	1.3	0.62		
						AC & WC	1.7	0.59		
				14.0	0.00	AC	1.2	0.42	8.5	0.00
	Winter	1.2	0.51			Heater & WC	1.2	0.47		
						No Heater & No WC	1.2	0.61		
Air Problems	Summer	3.0	1.55			Fan & WC	2.8	1.49		
						AC & WC	3.6	1.32		
				16.8	0.00	AC	2.9	1.77	10.5	0.00
	Winter	2.4	1.4			Heater & WC	2.2	1.34		
						No Heater & No WC	3.1	1.4		
Air Feel	Summer	4.7	1.36			Fan & WC	4.3	1.47		
						AC & WC	5.6	0.82		
				26.8	0.00	AC	4.7	1.17	17.1	0.00
	Winter	3.9	1.6			Heater & WC	3.7	1.67		
						No Heater & No WC	4.6	1.12		
Physical Health	Summer	1.7	0.87			Fan & WC	1.6	0.87		
						AC & WC	1.6	0.79		
				3.7	0.06	AC	1.8	0.92	4.6	0.00
	Winter	1.5	0.71			Heater & WC	1.6	0.75		
						No Heater & No WC	1.2	0.39		

Var	Seasons	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*	Ventilation Mode	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*
Mental Health	Summer	1.8	0.9			Fan & WC	1.7	0.87		
						AC & WC	1.8	0.88		
				3.4	0.07	AC	2.1	0.93	6.2	0.00
	Winter					Heater & WC	1.8	0.81		
						No Heater & No WC	1.3	0.6		
Job Ability	Summer	1.6	0.79			Fan & WC	4.0	1.93		
						AC & WC	4.7	1.15		
				0.0	0.90	AC	4.1	1.29	1.7	0.16
	Winter					Heater & WC	4.2	1.48		
						No Heater & No WC	4.3	2.13		
Indoor Meeting	Summer	4.2	1.66			Fan & WC	2.0	0.86		
						AC & WC	1.2	0.37		
				0.7	0.41	AC	1.2	0.53	19.1	0.00
	Winter					Heater & WC	1.6	0.72		
						No Heater & No WC	1.3	0.47		
Indoor Office	Summer	1.5	0.68			Fan & WC	1.8	0.83		
						AC & WC	1.2	0.42		
				0.6	0.43	AC	1.4	0.67	8.5	0.00
	Winter	1.5	0.65			Heater & WC	1.6	0.69		
						No Heater & No WC	1.3	0.47		

Note: p <0.05; F > 5; (±SD) <1

The comparison of IAQ satisfaction for ventilation modes in summer was significant (p <0.05) for the indoor meetings (F 19.1), air feel (F 17.1), air problem (F 10.5), worriedness (F 8.5), indoor office conditions (F 8.5) and mental health (F 6.2), except the employee's ability to do the office task (p >0.05, F <5). Within the ventilation modes, all the groups with a mean satisfaction score of [1.2 (±0.51)] were worried about the air quality except the employees of 'air-conditioned and wind chimney'. The mean vote of (1.2) for the offices of 'air-conditioned and wind chimney', 'air-conditioned' and 'no heater and no wind chimney' showed employees' high satisfaction during meetings, compared to offices with 'fan and air-conditioned' [2 (±0.86)] in summer and 'heater and wind chimney' [1.6 (±0.72)] during winter. Most employees felt neutral about indoor air with a mean vote for 'heater and wind chimney' [3.7 (±1.67)], slightly stuffy for 'fan and wind chimney' [4.3 (±1.47)], 'no heater and wind chimney' [4.6 (±1.12)], 'air-conditioned' [4.7(±1.17)] and stuffy for 'air-conditioned and wind chimney' [5.6 (±0.82)].

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

However, the results were inconsistent with the large sample survey of thermal comfort and IAQ, showing that 69% of employees were satisfied and 26% of buildings met ASHRAE 62.1 standard [52] . The comparison of results between groups revealed air problems of mouldy odour and visible mould in the office of 'heater and wind chimney' [2.2 (±1.34)], chemical odour for 'no heater and no wind chimney' [3.1 (±1.4)], 'fan and wind chimney' [2.8 (±1.49)], 'air-conditioned' [2.9 (±1.77)] and dust in the indoor air for 'air-conditioned and wind chimney' [3.6 (±1.32)]. The employees in 'air-conditioned and wind chimney', 'no heater and no wind chimney' and 'air-conditioned' were satisfied with the indoor conditions during office tasks compared to 'heater and wind chimney' and 'fan and wind chimney'. Only the employees of 'no heater and no wind chimney' [1.3 (±0.6)] perceived that their physical and mental health was affected due to poor IAQ compared to other offices.

Indoor Air Quality Preferences

The air quality preferences were significant ($p < 0.05$) in both summer and winter for ventilation control, air refreshing measures, spray disinfection and air freshener (*Table 6)*. The employees' perception of air quality preference has a high F (22.13) and mean vote [3.87 (±1.01)] in summer compared to winter 3.33 (±1.25). The use of spray disinfection F (14.81) in offices was preferable to the air freshener (7.39) due to the dengue spray in offices. Also, the spray [2.4(±0.73)] and air freshener [2.4(±0.74)] filtration measures in offices were used more consistently in summer than in winter. However, the study showed insignificant ($p > 0.05$) results for 'door and windows, 'air purifiers' and 'indoor plants' for all offices.

Table 6 Descriptive Statistics and ANOVA Result of IAQ Preference

Var	Seasons	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*	Ventilation Mode	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*
Air Quality Preference	Summer	3.87	1.01	22.13	0.00	Fan & WC	3.7	1.05	18.77	0.00
						AC & WC	4.2	0.96		
						AC	3.8	0.91		
	Winter	3.33	1.25			Heater & WC	3.0	1.22		
						No Heater & No WC	4.2	0.89		
Door & Windows	Summer	1.69	0.62	0.65	0.42	Fan & WC	1.7	0.65	1.45	0.22
						AC & WC	1.6	0.67		
						AC	1.8	0.5		
	Winter	1.64	0.63			Heater & WC	1.6	0.64		
						No Heater & No WC	1.8	0.59		
Disinfect	Summer	2.4	0.73	14.81	0.00	Fan & WC	2.5	0.72	4.9	0.00
						AC & WC	2.5	0.71		
						AC	2.2	0.74		
	Winter	2.12	0.72			Heater & WC	2.1	0.75		
						No Heater & No WC	2.2	0.61		

Var	Seasons	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*	Ventilation Mode	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*
Air Freshener	Summer	2.46	0.74	7.39	0.01	Fan & WC	2.5	0.78	3.04	0.02
						AC & WC	2.6	0.49		
						AC	2.3	0.84		
	Winter	2.25	0.819			Heater & WC	2.2	0.83		
						No Heater & No WC	2.3	0.8		
Air Purifier	Summer	2.37	0.777	0	0.95	Fan & WC	2.6	0.66	6.73	0.00
						AC & WC	2.2	0.83		
						AC	2.0	0.75		
	Winter	2.37	0.846			Heater & WC	2.4	0.83		
						No Heater & No WC	2.2	0.89		
Plant	Summer	1.97	0.897	0	1.00	Fan & WC	2.3	0.91	6.19	0.00
						AC & WC	1.7	0.8		
						AC	1.7	0.8		
	Winter	1.97	0.807			Heater & WC	2.0	0.86		
						No Heater & No WC	1.8	0.6		

Note: $p < 0.05$; $F > 5$; (±SD) <1

The comparison of results between the ventilation modes in offices showed significant results ($p < 0.05$) with high F-value for air quality preference (18.77), air purifier (6.73), plant filtrations (6.19) and disinfection (5). Amongst the ventilation modes, the mean satisfaction in 'no heater and no wind chimney' [4.2 (± 0.89)], and 'heater and wind chimney' [3 (± 1.22)] showed that employees' air quality preference was unacceptable and neutral respectively. The employees occasionally preferred the filtration measures of air purifier, disinfection and plants in 'air-conditioned and wind chimney', 'fan and wind chimney' and 'air-conditioned and wind chimney'. However, due to running costs, the employees preferred plant [54] over air purifiers for pollutant mitigation. [55]

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

Thermal Satisfaction

The thermal satisfaction within the offices was measured and significant (p <0.05) for clothing F (229.70), temperature feel F (23.68), window size F (14.88), comfort F (7.9) and humidity feel F (6.8) as shown in *Table 7*. The employees were thermally satisfied in offices during summer with a neutral feel of temperature [-0.06 (±2.01)], slightly disagree for window size [4.78 (±1.94)], just right comfort [0.67 (±1.89)] and less humid [0.15 (±2.06)] conditions. In winter, thermal satisfaction was achieved with thick clothing [1.6 (±0.16)], and employees felt neutral temperature [-0.06 (±2.01)], quite disagree with window size [5.47 (± 1.61)], less humid [0.15 (±2.06)], but comfortable [0.66 (±1.73)] in offices.

Table 7 Descriptive Statistics and ANOVA Result of Thermal Satisfaction

Var	Seasons	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*	Ventilation Mode	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*
Clothing	Summer	1.38	0.13	229.70	0.00	Fan & WC	1.4	0.14	92.64	0.00
						AC & WC	1.4	0.12		
						AC	1.4	0.12		
	Winter	1.6	0.16			Heater & WC	1.7	0.12		
						No Heater & No WC	1.4	0.17		
Activity	Summer	1.28	0.35	0.29	0.59	Fan & WC	1.3	0.36	21.43	0.00
						AC & WC	1.6	0.3		
						AC	1.1	0.1		
	Winter	1.3	0.33			Heater & WC	1.3	0.3		
						No Heater & No WC	1.5	0.38		
Window Size	Summer	4.78	1.94	14.88	0.00	Fan & WC	4.6	1.95	4.54	0.00
						AC & WC	4.8	1.76		
						AC	5.0	2.09		
	Winter	5.47	1.61			Heater & WC	5.4	1.68		
						No Heater & No WC	5.8	1.34		
Temperature Feel	Summer	0.91	1.91	23.68	0.00	Fan & WC	1.4	1.64	15.41	0.00
						AC & WC	1.3	2.13		
						AC	-0.5	1.52		
	Winter	-0.06	2.01			Heater & WC	0.0	1.97		
						No Heater & No WC	-0.3	2.13		

Var	Seasons	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*	Ventilation Mode	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*
Humidity Feel	Summer	0.67	1.89	6.8	0.01	Fan & WC	0.6	2.08	3.94	0.00
						AC & WC	0.7	1.62		
						AC	0.8	1.75		
	Winter	0.15	2.06			Heater & WC	-0.1	2.05		
						No Heater & No WC	0.4	1.99		
Air Flow Feel	Summer	0.19	2.12	1.48	0.23	Fan & WC	-0.3	2.17	4.31	0.00
						AC & WC	0.7	2.14		
						AC	0.7	1.72		
	Winter	0.43	1.68			Heater & WC	0.5	1.77		
						No Heater & No WC	0.4	1.41		
Comfort Feel	Summer	0.13	2	7.90	0.01	Fan & WC	0.0	2.11	7.30	0.00
						AC & WC	0.8	1.91		
						AC	-0.2	1.71		
	Winter	0.66	1.73			Heater & WC	0.9	1.72		
						No Heater & No WC	-0.1	1.51		
Acceptability of Thermal Environment	Summer	3.66	1	4.62	0.03	Fan & WC	3.4	1.12	6.67	0.00
						AC & WC	4.0	0.84		
						AC	3.9	0.68		
	Winter	3.44	1.02			Heater & WC	3.5	0.92		
						No Heater & No WC	3.2	1.27		

Note: p <0.05; F > 5; (±SD) <1

Within the ventilation modes, the thermal satisfaction was significant (p <0.05) for clothing (F 92.64), activity (F 21.43), temperature feel (F 15.41), comfort feel (F 7.30) and acceptability of thermal environment (F 6.67). The employees felt slightly warm [1.4 (±1.64)] in offices of 'fan and wind chimney', 'air-conditioned and wind chimney' and slightly cool in 'air-conditioned' [-0.5 (±1.52)], felt neutral in 'heater and wind chimney' and 'no heater and no wind chimney'. The comfort feel was 'just Right' in 'fan and Wind chimney' and a little comfortable in 'air-conditioned and wind chimney' [0.8 (±1.91)] and 'heater and wind chimney' [0.9 (±1.72)], a little uncomfortable in offices of 'air-conditioned' [-0.2 (±1.71)] and 'no heater and no wind chimney' [-0.1 (±1.51)]. For the thermal acceptability of the environment, the employees felt neutral in offices with 'no heater and no wind chimney' [3.2 (±1.27)], 'fan and wind chimney' [3.4 (±1.12)] whereas unacceptable in 'heater and wind chimney' [3.5 (±0.92)], 'air-conditioned' [3.9 (±0.68)], 'air-conditioned and wind chimney' [4 (±0.84)] and may tend to change their thermal state.

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

Thermal Preference

The thermal preferences were significant ($p < 0.05$) and different in summer and winter, for the airy office (F 61.46), the expectation of temperature state (F 35.25), the draught feel (F 17.01) and humidity feel for opened window (F 7.95) (*Table 8)*. The employees preferred an airy office [-1.9 (±1.5)], desired a cooler state [-0.87 (±1.71)], did not feel draught [4.12 (±1.99)] and neutral humidity feels [0.14 (±1.79)] in summer. During winter, the employees preferred the least airy [-0.69 (±1.54)], expected a neutral temperature state [-0.87 (±2.52)], less draughty [3.33 (±1.80)] and just right humidity feel [-0.35 (±1.61)].

The thermal preference was significant at $p < 0.05$, with an F-value for 'airy office' (24.11), the 'expectation of temperature state' (11.23), 'humidity preference' (6.89) and 'window draught' (5.1). The employees preferred least airy for 'air-conditioned and wind chimney' [-1.3 (±1.8)] and 'no heater and no wind chimney' [-1.5 (±1.42)] and neutral for 'heater and wind chimney' [-0.4(±1.5)] but did not prefer an airy office for 'air-conditioned' [-2.4 (±0.83)] and 'fan and wind chimney' [-2 (±1.51)]. The employees expected to achieve a temperature state of neutral for 'heater and wind chimney' [-0.7 (±2.58)], cooler for 'fan and wind chimney' [-2.2 (±1.8)], 'air-conditioned and wind chimney' [-2.7 (±0.48)] and warmer for 'air-conditioned' [-1.6 (±2.12)], 'heater and wind chimney' [-0.7 (±2.58)] and 'no heater and No wind chimney' [-1.4 (±2.28)]. The humidity and window draught were preferred neutral for all ventilation modes except the employees favoured less humid in 'air-conditioned and wind chimney' [1.4 (±1.77)]. The neutral feel in all ventilation modes for humidity and air draught represents the state of neither too strong nor too weak, with minimum discomfort and enhanced IAQ.

Table 8 Descriptive Statistics and ANOVA Result of Thermal Preference

Var	Seasons	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*	Ventilation Mode	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*
Office Airy	Summer	-1.9	1.50	61.46	0.00	Fan & WC	-2.0	1.51	24.11	0.00
						AC & WC	-1.3	1.8		
						AC	-2.4	0.83		
	Winter	-0.69	1.54			Heater & WC	-0.4	1.5		
						No Heater & No WC	-1.5	1.42		
Humidity Preference	Summer	0.37	2.03	0.03	0.87	Fan & WC	-0.2	1.9	6.89	0.00
						AC & WC	1.4	1.77		
						AC	0.5	2.18		
	Winter	0.4	1.54			Heater & WC	0.3	1.61		
						No Heater & No WC	0.8	1.26		
Temperature State Expectation	Summer	-2.16	1.71	35.25	0.00	Fan & WC	-2.2	1.8	11.23	0.00
						AC & WC	-2.7	0.48		
						AC	-1.6	2.12		
	Winter	-0.87	2.52			Heater & WC	-0.7	2.58		
						No Heater & No WC	-1.4	2.28		

Var	Seasons	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*	Ventilation Mode	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*
Window Office Draught	Summer	4.12	1.99	17.01	0.00	Fan & WC	4.1	2.12	5.1	0.00
						AC & WC	4.1	1.8		
						AC	4.2	1.94		
	Winter	3.33	1.80			Heater & WC	3.5	1.79		
						No Heater & No WC	2.9	1.79		
Window Office Humidity	Summer	0.14	1.79	7.95	0.01	Fan & WC	0.1	1.87	3.9	0.00
						AC & WC	-0.2	1.71		
						AC	0.7	1.61		
	Winter	-0.35	1.61			Heater & WC	-0.3	1.62		
						No Heater & No WC	-0.5	1.58		

Note: p <0.05; F > 5; (±SD) <1

Health Symptoms

The office syndromes were significant ($p < 0.05$) for the stuffed nose (F 56.46), sore throat (F 53.26), dry throat (F 36.24), headache (F 35.45), running nose (F 33.04), low morale (F 25.02), hand rash (F 25.28), drowsiness (F 23.84), low morale (F 25.02), swallow eyelid (F 21.94), lack of concentration (F 20.06), eye irritation (F 14.93), face rash (F 8.64) and skin redness (F 8.05) but insignificant for skin itching (*Table 9*). The average mean satisfaction of voting ranged between 2 - 2.5 were the frequently occurring health symptoms. The mean satisfaction votes in winter for physiological symptoms of hand rash, skin redness, runny nose, stuffed

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

nose, eye irritation and sore throat, psychological symptoms of low morale, and headache suggested that the employees frequently experienced these symptoms because of switching between air-conditioned and non-air-conditioned environments causing sick building syndromes (SBS). [56,57] The mean suggested the frequent occurrence of dry throat and reduced productivity during summer and winter in offices. The findings agreed with Norback and Fu [48,58] that environment and workplace could cause sick building syndrome for office employees.

Table 9 Descriptive Statistics and ANOVA Result of Health Symptoms

Var	Seasons	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*	Ventilation Mode	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*
Eye Irritation	Summer	2.5	0.59	14.93	0.00	Fan & WC	2.4	0.6	8.79	0.00
						AC & WC	2.8	0.4		
						AC	2.5	0.6		
	Winter	2.23	0.76			Heater & WC	2.3	0.7		
						No Heater & No WC	2.0	0.8		
Swollen Eyelid	Summer	2.84	0.47	21.94	0.00	Fan & WC	2.8	0.5	9.49	0.00
						AC & WC	2.9	0.2		
						AC	2.8	0.5		
	Winter	2.57	0.68			Heater & WC	2.7	0.7		
						No Heater & No WC	2.3	0.7		
Running Nose	Summer	2.63	0.60	33.04	0.00	Fan & WC	2.7	0.6	13.64	0.00
						AC & WC	2.6	0.5		
						AC	2.5	0.7		
	Winter	2.22	0.78			Heater & WC	2.3	0.7		
						No Heater & No WC	1.9	0.9		
Stuffed Nose	Summer	2.65	0.62	56.46	0.00	Fan & WC	2.6	0.7	14.16	0.00
						AC & WC	2.7	0.6		
						AC	2.6	0.6		
	Winter	2.14	0.71			Heater & WC	2.2	0.7		
						No Heater & No WC	2.1	0.7		
Dry Throat	Summer	2.29	0.765	36.24	0.00	Fan & WC	2.4	0.8	12.84	0.00
						AC & WC	2.5	0.6		
						AC	2.0	0.9		
	Winter	1.83	0.73			Heater & WC	1.9	0.8		
						No Heater & No WC	1.7	0.7		
Sore Throat	Summer	2.59	0.65	53.26	0.00	Fan & WC	2.6	0.7	14.64	0.00
						AC & WC	2.7	0.5		
						AC	2.5	0.7		
	Winter	2.07	0.76			Heater & WC	2.1	0.7		
						No Heater & No WC	1.9	0.9		
Hand Rash	Summer	2.79	0.52	25.28	0.00	Fan & WC	2.7	0.6	8.28	0.00
						AC & WC	2.9	0.2		
						AC	2.8	0.6		
	Winter	2.46	0.75			Heater & WC	2.5	0.7		
						No Heater & No WC	2.3	0.8		
Face Rash	Summer	2.76	0.61	8.64	0.00	Fan & WC	2.7	0.6	8.15	0.00
						AC & WC	2.8	0.5		
						AC	2.8	0.7		
	Winter	2.57	0.66			Heater & WC	2.7	0.5		
						No Heater & No WC	2.2	0.9		
Skin Itching	Summer	2.63	0.62	2.45	0.12	Fan & WC	2.5	0.7	6.75	0.00
						AC & WC	2.8	0.4		
						AC	2.7	0.6		
	Winter	2.53	0.67			Heater & WC	2.6	0.5		
						No Heater & No WC	2.2	0.9		

Var	Seasons	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*	Ventilation Mode	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*
Skin Redness	Summer	2.61	0.70	8.05	0.01	Fan & WC	2.6	0.8	6.55	0.00
						AC & WC	2.8	0.4		
						AC	2.5	0.8		
	Winter	2.4	0.76			Heater & WC	2.5	0.7		
						No Heater & No WC	2.1	0.9		
Headache	Summer	2.35	0.66	35.45	0.00	Fan & WC	2.5	0.6	13.58	0.00
						AC & WC	2.3	0.6		
						AC	2.2	0.7		
	Winter	1.96	0.65			Heater & WC	2.1	0.7		
						No Heater & No WC	1.7	0.5		
Reduced Productivity	Summer	2.48	0.71	5.62	0.02	Fan & WC	2.6	0.7	4.98	0.00
						AC & WC	2.5	0.6		
						AC	2.2	0.8		
	Winter	2.31	0.70			Heater & WC	2.4	0.7		
						No Heater & No WC	2.1	0.7		
Low Morale	Summer	2.64	0.65	25.02	0.00	Fan & WC	2.7	0.6	19.78	0.00
						AC & WC	2.8	0.6		
						AC	2.4	0.8		
	Winter	2.3	0.72			Heater & WC	2.5	0.7		
						No Heater & No WC	1.8	0.6		
Drowsiness	Summer	2.6	0.68	23.84	0.00	Fan & WC	2.7	0.6	12.49	0.00
						AC & WC	2.7	0.6		
						AC	2.2	0.8		
	Winter	2.23	0.78			Heater & WC	2.3	0.8		
						No Heater & No WC	2.0	0.8		
Lack of Concentration	Summer	2.58	0.66	20.06	0.00	Fan & WC	2.5	0.7	6.01	0.00
						AC & WC	2.7	0.5		
						AC	2.5	0.7		
	Winter	2.27	0.70			Heater & WC	2.3	0.8		
						No Heater & No WC	2.3	0.5		
Dust Allergy Symptoms	Summer	2.27	0.76	5.45	0.02	Fan & WC	2.2	0.8	3.21	0.01
						AC & WC	2.4	0.8		
						AC	2.3	0.7		
	Winter	2.09	0.76			Heater & WC	2.0	0.8		
						No Heater & No WC	2.2	0.8		
Seasonal Health	Summer	1.92	0.74	6.29	0.01	Fan & WC	1.9	0.7	2.48	0.04
						AC & WC	1.9	0.8		
						AC	1.9	0.7		
	Winter	1.69	1.01			Heater & WC	1.8	1		
						No Heater & No WC	1.5	0.9		

Note: $p < 0.05$; $F > 5$; (±SD) <1

Within ventilation modes the employees reported significant ($p < 0.05$) results for physiological health of sore throat (F 14.64), stuffed nose (F 14.16), runny nose (F 13.64), headache (F 13.58), dry throat (F 12.84), swollen eyelid (F 9.49), eye irritation (F 8.79), hand rash (F 8.28), face rash (F 8.15), skin itching (F 6.75), skin redness (F 6.55) and psychological symptoms of low morale (F 19.78), drowsiness (F 12.49), and lack of concentration (F 6.01). Employees frequently reported eye irritation and dry throat in the ‘fan and wind chimney’ office, faced headaches in the ‘air-conditioned and wind chimney’ office and suffered frequent drowsiness, low morale, reduced productivity and headaches in the ‘air-conditioned’ offices. Employees face thermal shifts between air-conditioned and non-air-conditioned environments and different ventilation modes [59]. In the ‘heater and wind chimney’ office, the employee faced the physiological issues of eye irritation, running nose, stuffed nose, dry throat, sore throat, and

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

psychological symptoms of headache, drowsiness and lack of concentration that further caused hypertension and cardiovascular illness. [60] For 'no heater and no wind chimney,' the employees frequently faced eye irritation, swollen eyelid, respiratory illness of sore throat, stuffed nose, and runny nose, dry throat, sore throat, dermatological issues of hand rash, face rash, skin itching, and skin redness, felt low morale and psychological symptoms of headache, reduced productivity, low morale, drowsiness and lack of concentration. The sick building health symptoms in office workers are caused by the persistent effects of illness, pollutant concentration [61] and changes in the thermal environment during winter and summer. It has been concluded that the SBS effect is more in the 'no heater and no wind chimney' office than the 'air-conditioned' office during winter and summer respectively.

Filtration

Employees' perception of "filtration" in offices was significant ($p > 0.05$) for the table (F 16.49), hanging pots (F 15.32), plant preference (F 939) and plant boasting energy and creativity (F 8.28) (*Table 10)*. The employees preferred the indoor natural plants [1.1 (±0.21)] during summer and winter because of the positive impact of indoor plants, boost positive energy and creative ideas [5.93 (±1.45)], quite agreed for table pots [5.5 (±1.71)] and hanging pots [5.5 (±1.78)] in winter.

Table 10 Descriptive Statistics and ANOVA Result of Filtration

Var	Seasons	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*	Ventilation Mode	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*
Indoor Plant Role	Summer	5.6	1.82	1.12	0.29	Fan & WC	5.4	2.01	2.23	0.07
						AC & WC	5.5	1.47		
						AC	6.1	1.68		
	Winter	5.8	1.39			Heater & WC	5.8	1.46		
						No Heater & No WC	5.5	1.14		
Plant Preference	Summer	1.1	0.21	9.39	0.00	Fan & WC	1.1	0.26	4.31	0.00
						AC & WC	1.0	0.20		
						AC	1.0	0.00		
	Winter	1.0	0			Heater & WC	1.0	0.00		
						No Heater & No WC	1.0	0.00		
Business Success	Summer	2.3	1.44	0.62	0.43	Fan & WC	2.5	1.58	1.04	0.39
						AC & WC	2.3	1.35		
						AC	2.0	1.18		
	Winter	2.4	1.51			Heater & WC	2.4	1.61		
						No Heater & No WC	2.4	1.13		
Customers Feedback	Summer	5.3	1.69	1.39	0.24	Fan & WC	5.1	1.95	2.24	0.06
						AC & WC	5.7	1.32		
						AC	5.4	1.38		
	Winter	5.5	1.73			Heater & WC	5.4	1.89		
						No Heater & No WC	5.9	1.07		
Table Pots	Summer	4.8	1.80	16.49	0.00	Fan & WC	4.5	1.93	7.74	0.00
						AC & WC	5.5	1.26		
						AC	4.7	1.81		
	Winter	5.5	1.71			Heater & WC	5.4	1.82		
						No Heater & No WC	5.8	1.27		
Hanging Pots	Summer	4.7	1.89	15.32	0.00	Fan & WC	4.7	2.01	5.01	0.00
						AC & WC	4.9	1.79		
						AC	4.7	1.75		
	Winter	5.5	1.78			Heater & WC	5.3	1.92		
						No Heater & No WC	5.9	1.15		
Energy & Creativity	Summer	5.9	1.45	8.28	0.00	Fan & WC	5.9	1.49	2.57	0.04
						AC & WC	6.0	1.14		
						AC	6.0	1.65		
	Winter	5.5	1.70			Heater & WC	5.4	1.83		
						No Heater & No WC	5.7	1.21		

Note: $p < 0.05$; $F > 5$; (±SD) < 1

The comparison of ventilation modes showed significant ($p < 0.05$) results for table pots (F 7.74) and hanging pots (F 5.01) as effective filtration methods. However, people likely opted for indoor plantation measures within offices to manage IAQ. Amongst the ventilation modes, the employees quite disagreed with tabletop plants in 'no heater and no wind chimney', [5.8 (±1.27)], 'air-conditioned and wind chimney' [5.5 (±1.26)], but neither agreed nor disagreed with the presence of tabletop plants in 'heater and wind chimney' [5.4 (±1.82)], 'air-conditioned' [4.7(±1.81)] and 'fan and wind chimney' [4.5(±1.93)]. The employees quite disagreed having hanging pots for 'no heater and no wind chimney' [5.9 (±1.15)], slightly disagreed for 'heater and wind chimney' [5.3 (±1.92)], 'air-conditioned and wind chimney' [4.9 (±1.79)], 'air-conditioned' [4.7 (±1.75)] and 'fan and wind chimney' [4.7 (±2.01)].

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

Wind Catcher Familiarity

The surveyed results were insignificant (p > 0.05) for wind catcher designs of the modular, tower, open, closed scoop, traditional, contemporary and modern classifications *(Table 11)*. There was not much difference between employees' opinions during summer and winter for various wind catcher designs and the observed difference in the mean for all wind catcher types was merely due to chance. The results were reaffirmed with an F (2-5) for wind catcher types and employees' perception remained the same with the least difference during summer and winter. The observed differences were due to the existing wind chimneys not working and having limited decorative use in current practices.

Table 11 Descriptive Statistics and ANOVA Result of Wind Catcher Familiarity

Var	Seasons	Descriptive		ANOVA		Ventilation Mode	Descriptives		ANOVA		Var	Seasons	Descriptives		ANOVA		Ventilation Mode	Descriptives		ANOVA	
		Mean	±SD	F	Sig.*		Mean	±SD	F	Sig.*			Mean	±SD	F	Sig.*		Mean	±SD	F	Sig.*
Modular	Summer	1.6	0.73			Fan & WC	1.6	0.74			Open Scoop	Summer	1.9	0.66			Fan & WC	2.1	0.65		
						AC & WC	1.6	0.76									AC & WC	1.7	0.65		
				3.53	0.06	AC	1.6	0.67	0.98	0.42					0.19	0.67	AC	1.8	0.59	3.04	0.02
	Winter	1.5	0.73			Heater & WC	1.5	0.74				Winter	1.9	0.75			Heater & WC	1.9	0.79		
						No Heater & No WC	1.5	0.68									No Heater & No WC	1.8	0.6		
Scoop	Summer	2.0	0.54			Fan & WC	2.1	0.46			Traditional Tower	Summer	1.4	0.68			Fan & WC	1.6	0.8		
						AC & WC	1.8	0.7									AC & WC	1.4	0.57		
				2.61	0.11	AC	2.1	0.47	2.76	0.03					0.02	0.89	AC	1.1	0.35	8.9	0.00
	Winter	1.9	0.65			Heater & WC	1.9	0.67				Winter	1.4	0.71			Heater & WC	1.3	0.6		
						No Heater & No WC	1.9	0.55									No Heater & No WC	1.8	0.89		
Contemporary	Summer	1.5	0.71			Fan & WC	1.6	0.72			Modern Tower	Summer	1.8	0.70			Fan & WC	1.9	0.76		
						AC & WC	1.4	0.57									AC & WC	1.6	0.68		
				0.01	0.95	AC	1.5	0.82	0.93	0.45					0.59	0.45	AC	1.8	0.54	4.40	0.00
	Winter	1.5	0.74			Heater & WC	1.5	0.72				Winter	1.7	0.75			Heater & WC	1.6	0.81		
						No Heater & No WC	1.6	0.81									No Heater & No WC	2.0	0.46		

Note: p <0.05; F > 5; (±SD) <1

The ventilation mode comparison showed significant results (p <0.05) for the open, closed scoop, traditional and modern towers. However, only the traditional wind tower (F 8.9) showed a difference in employees' opinions about familiarity. The employees of 'air-conditioned and wind chimney' [1.4 (±0.57)], 'heater and wind chimney' [1.3 (±0.6)] and 'air-conditioned' [1.1 (±0.35)] are familiar with the traditional tower of Iran but unfamiliar for the employees of 'no heater and no wind chimney' [1.8 (±0.89)], and 'fan and wind chimney' [1.6 (±0.8)].

Wind Catcher Preference

The wind catcher preference was significant (p < 0.05) for passive ventilation (F 17.2), cultural association (F 17.6), and factory installation (F 9.4) *(Table 12)*. The mean vote suggested that the employees quite agreed to make a passive ventilation/use of wind energy for modern wind catcher applications [6.04 (±1.33)] in summer than winter [5.4 (±1.7)]. The workers associate more cultural and traditional associations with wind catchers in winter [5.1 (±2.0)] than in summer [4.3 (±2.1)]. The employees' preference for factory-manufactured wind catcher installation was higher in summer [1.6 (±0.9)].

The comparison of ventilation modes for the wind catcher preference showed significant results (p < 0.05) for wind catcher passive use (F 9.77), and its potential applicability (F 5.68). The employees agreed with the passive use of wind energy for modern wind catchers in 'no heater and no wind chimney' [6.49 (±0.94)], quite agreed in 'heater and wind chimney' [5.88 (±1.41)], 'air-conditioned' [5.67 (±1.13)], 'fan and wind chimney' [5.61 (±1.76)] and neither agreed nor

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

disagreed in 'air-conditioned and wind chimney' [4.67 (±1.93)]. The employees chose that the wind catchers were potentially applicable to offices of 'fan and wind chimney' [1.42 (±0.75)], 'no heater and no wind chimney' [1.2 (±0.61)], 'air-conditioned and wind chimney' [1.12 (±0.33)] and did not perceive applicable by the employees of 'air-conditioned' [1.63 (±0.91)], 'heater and wind chimney' [1.58 (±0.8)]. Most people anticipated that it would be hard to perceive the functional aspect of wind catchers. This reaffirmed the findings that a full range of attributes of wind catcher design, and user perception for positive and negative socio-economic issues [62] be considered to reduce pollutants and achieve optimum humidity and temperature.

Table 12 Descriptive Statistics and ANOVA Result of Wind Catcher Preference

Var	Seasons	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*	Ventilation Mode	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*
Passive Use	Summer	5.4	1.7	17.2	0.00	Fan & WC	5.61	1.76	9.77	0.00
						AC & WC	4.67	1.93		
						AC	5.67	1.13		
	Winter	6.0	1.3			Heater & WC	5.88	1.41		
						No Heater & No WC	6.49	0.94		
Natural Ventilation	Summer	5.8	1.5	2.6	0.11	Fan & WC	6.01	1.54	2.5	0.04
						AC & WC	5.2	1.73		
						AC	5.86	1.1		
	Winter	5.5	1.9			Heater & WC	5.49	1.93		
						No Heater & No WC	5.49	1.84		
Cultural Association	Summer	4.3	2.1	17.6	0.00	Fan & WC	4.33	2.18	4.99	0.00
						AC & WC	4.06	1.92		
						AC	4.29	2.08		
	Winter	5.1	2.0			Heater & WC	5.22	1.94		
						No Heater & No WC	4.78	1.97		
Dust Filtration	Summer	5.1	1.6	2.2	0.14	Fan & WC	5	1.76	0.9	0.46
						AC & WC	5.31	1.47		
						AC	5.22	1.25		
	Winter	5.4	1.8			Heater & WC	5.35	1.82		
						No Heater & No WC	5.47	1.71		

Var	Seasons	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*	Ventilation Mode	Descriptives Mean	Descriptives ±SD	ANOVA F	ANOVA Sig.*
Smart Wind Catcher	Summer	1.4	0.8	1.6	0.21	Fan & WC	1.45	0.79	3.12	0.02
						AC & WC	1.16	0.51		
						AC	1.59	0.89		
	Winter	1.3	0.7			Heater & WC	1.36	0.7		
						No Heater & No WC	1.2	0.61		
Potential Applicability	Summer	1.4	0.7	1.3	0.26	Fan & WC	1.42	0.75	5.68	0.00
						AC & WC	1.12	0.33		
						AC	1.63	0.91		
	Winter	1.5	0.8			Heater & WC	1.58	0.8		
						No Heater & No WC	1.2	0.61		
Factory Manufactured	Summer	1.6	0.9	9.4	0.00	Fan & WC	1.51	0.85	3.14	0.02
						AC & WC	1.71	0.91		
						AC	1.69	0.96		
	Winter	1.4	0.7			Heater & WC	1.35	0.62		
						No Heater & No WC	1.41	0.81		

Note: $p < 0.05$; $F > 5$; (±SD) <1

Comparing the Groups for Performance Evaluation

The IAQ satisfaction of the sampled office was higher in summer than in winter when compared between seasons and within the ventilation modes. The IAQ preference was higher during summer compared to winter but similar when compared between seasons and within the ventilation modes. The employees achieved thermal satisfaction with thick clothing and preferred diverse activities in winter due to the temperature, humidity and acceptability of the thermal environment. Thermal preference was perceived as neutral for winter temperature, humidity and draught conditions. The more profound impact of physiological and psychological symptoms and their consequent health effects of SBS were faced during summer than winter. The existing filtration measures were preferred in winter due to poor air quality and the employees have less awareness of the wind catchers for both seasons but high preference during winter. The comparative analysis of ventilation modes showed more IAQ satisfaction in 'air-conditioned', and 'air-conditioned and wind chimney' as the employees perceived that air-conditioned filters would clean air and employees in offices with the 'fan and wind chimney' showed less IAQ satisfaction. During winter, the IAQ satisfaction was higher in the 'heater and wind chimney' office and the existing ventilation measures were preferred due to high and poor outdoor air quality index when compared within or between groups.

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

The graph of thermal comfort, acceptability of thermal environment and window ventilation were sorted by the building code for comparing ventilation modes. The preference for 'fan and wind chimney', air-conditioned' and 'wind chimney and air-conditioned' during summer and 'wind chimney and heater', 'no heater and no wind chimney' during winter were counted from the comfort votes.

Thermal Comfort

Thermal Comfort is an individual's physiological, behavioural and psychological response to their environment. [35] The survey measured thermal comfort as the individual response to the temperature, humidity, airflow sensation and comfort conditions *(Figure 16a-e*).

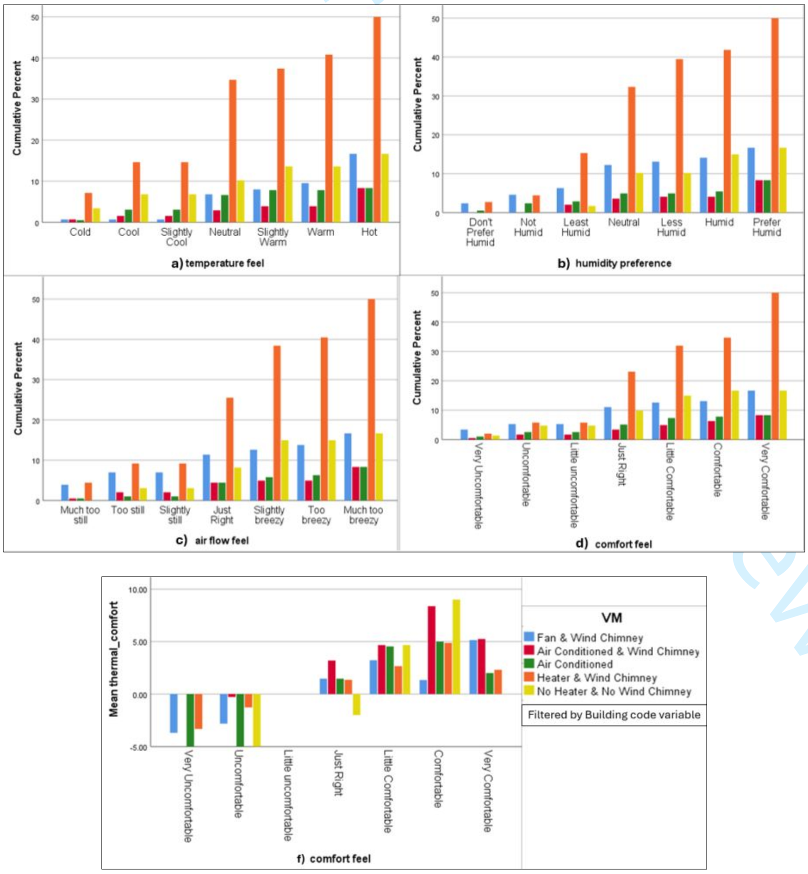


Figure 4 Thermal Comfort Variables for Five Ventilation Modes; a) Temperature Feel, b) Humidity Feel, c) Air flow Feel, d) Comfort Feel, e) Thermal comfort Votes

During summer and winter, most employees in the 'fan and wind chimney' and 'heater and wind chimney' reported discomfort and complained about the warm and hot conditions during

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

the two seasons. The employees faced humid conditions in all offices during summer and winter and the effect of airflow feel was higher in the 'fan and wind chimney' compared to the 'air-conditioned' offices in summer. During winter, employees in offices with wind chimney reported discomfort with much too breezy conditions. So, the cumulative average of comfortable feel was higher in 'fan and wind chimney' compared to non-wind chimney offices during summer and winter. The 'heater and wind chimney' were effective for a 'very comfortable' condition. The comfort was determined based on the combined effect of temperature, humidity, airflow and comfort feel. The 'fan and wind chimney' office was 'very comfortable' and had a 'comfortable' feel for the 'air-conditioned and wind chimney' office during summer. However, in winter, occupants in 'no heater and no wind chimney' office reported the most comfortable feel, with few employees being uncomfortable in all building types. The cumulative effect of thermal conditions, for the employees of offices were 'mostly comfortable' with the ventilation modes.

Thermal Acceptability

The employees' acceptability of the given thermal environment for five ventilation modes depended on the counted votes and adaptable measures of activities and clothing *(Figure 17a-c)*.

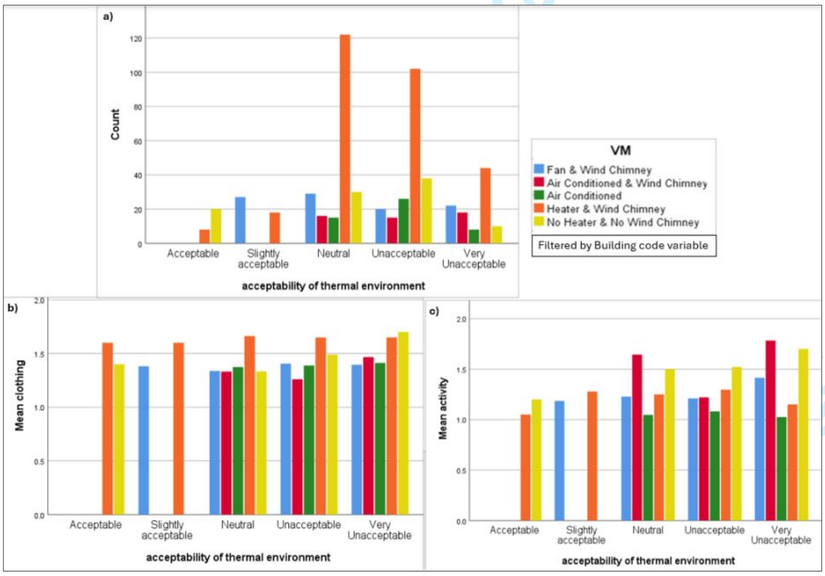


Figure 17 Thermal Acceptability for Five Ventilation Modes; a) Acceptability of Thermal Environment, b) Acceptability of Thermal Environment for clothing, c) Acceptability of Thermal Environment for activities

During winter, the employees in offices with different modes used adaptable clothing and activities to make the thermal environment acceptable. During summer, the employees in the 'fan & wind chimney' have mixed responses to the overall thermal environment. The

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

significant count of thermal environment acceptability in the ‘heater and wind chimney’ gave a neutral feel. The employees undertook various activities in the offices and the tasks were managed for 8 hours of activities. Most employees reported acceptability of the thermal environment in the ventilation modes undertaking high metabolic activities of writing (1.0 met) and typing (1.1 met). The employees of the ‘air-conditioned and wind chimney’ offices reported high acceptability for walking (1.7 met). The acceptability of the thermal environment with mean clothing greater than 1.5 was acceptable for winter ventilation modes. The employees of the offices wore clothing that gave them a neutral, unacceptable and very unacceptable feel.

Window Ventilation

Window ventilation depends on employees’ satisfaction with window size, incoming humidity and draught feel when it is open (*Figure 18a-c*). Most employees in offices with ‘fan and wind chimney’ disagreed with the given window size. For air-conditioned offices with or without a wind chimney, the effect of window size was limited to opening it often when electricity was out of supply or for natural light. The employees in offices with ‘heater and wind chimney’ and ‘no heater and no wind chimney’ disagreed with window size. During winter, employees in offices with ‘heater and wind chimney’ would require ‘fairly high’ humidity through the window, and in summer, employees of ‘fan and wind chimney’ complained of window humidity. The window office draught was frequently and ‘fairly’ experienced by employees of the ‘no heater and no wind chimney’ office. For offices with ‘fan and wind chimney’, the highest vote count for window draught was for ‘fan & wind chimney’ as neither or never experienced by employees.

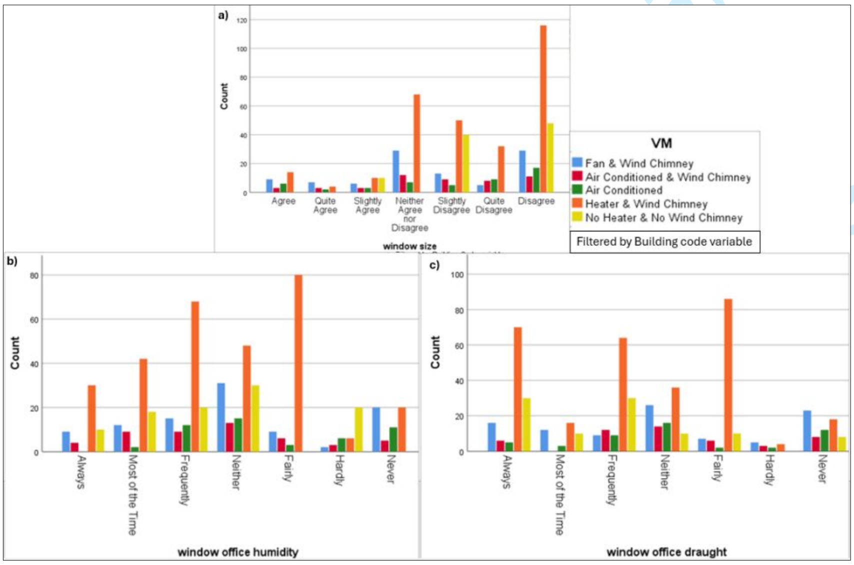


Figure 18 Wind Ventilation Variables for Ventilation Modes; a) Window Size, b) Window Office Humidity, c) Window Office Draught

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

During summer, higher thermal satisfaction and preference amongst employees compared to winter between and within the groups showed better thermal performance of wind chimneys. However, within ventilation modes, the low perception of thermal preference was reported for 'fan and wind chimney' with passive controls. The employees' subjective evaluation of the sampled office reported better health conditions in summer than in winter. The wind chimney offices were more helpful to employees in combination with other measures to achieve better health conditions within the offices. The employees of air-conditioned offices exhibited higher health scores because of thermal shifts when switching between air-conditioned and non-conditioned environments, causing SBS due to thermal comfort and IAQ management. [63]

The filtration methods of the indoor landscape were preferred by employees during summer than in winter, and results were akin to Yan, [64] which showed the impact of season on thermal comfort with landscape. The comparison of ventilation modes showed the highest appreciation of filtration measures reported by the employees of wind chimney offices than any other ventilation modes. The wind catcher familiarity was low in all groups except the wind chimney offices due to less awareness about passive measures and modern wind catcher designs. The employees preferred modern wind catchers during summer due to their experienced satisfaction with IAQ and thermal comfort. The employees in offices with 'fan and wind chimney', 'air-conditioned and wind chimney' and 'heater and wind chimney' had better thermal performance and IAQ. The wind chimneys were effective during summer and winter whereas the wind catchers were only used in summer. [65]

Employees scored high satisfaction in air-conditioned offices with or without wind chimneys because the air-conditioner filters the dust, improved the air quality and thermal comfort. However, the employees of sampled offices in Lahore did not express 80-90% thermal environment satisfaction as recommended by the comfort standards. [34,51,52] The existing trend indicated that the ventilation measures did not create a fully comfortable indoor environment in offices with 80-90 % thermal acceptability.

Comfort Indexes and Performance Evaluation of Ventilation Modes

The performance evaluation of the five ventilation modes was done with the CBE thermal comfort tool for calculating thermal comfort indexes [66] of the Predicted mean vote (PMV), the Predicted Percentage of Dissatisfied (PPD), the Standard Effective Temperature (SET) and Leadership in Energy and Environmental Design (LEED) Compliance *(Table 13)*. Generally, only GH (0.04, 5%), which have 'air-conditioned and wind chimney' achieved thermal neutrality and complied with the LEED standards during the winter *(Figure 19)*.

Table 13 CBE thermal comfort Tool [66] and LEED Compliance for offices

Ventilation Mode	Building Code	PMV	PPD	SET	LEED compliance
Air-conditioned	PSDA	-1.35	43	20.1	FALSE
Fan and wind chimney	DPI	-1.31	41	20.2	FALSE
	PCS	-2.18	84.2	17.3	FALSE
Air-conditioned and wind chimney	GH	-1.64	58.5	19.2	FALSE
No heater & No wind chimney	PSDA	-0.76	17.2	22.6	FALSE
Heater & wind chimney	PCS	1.54	53.3	30.7	FALSE
	GH	-0.04	5	25	**TRUE**
	DPI	2.43	91.8	33.2	FALSE

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

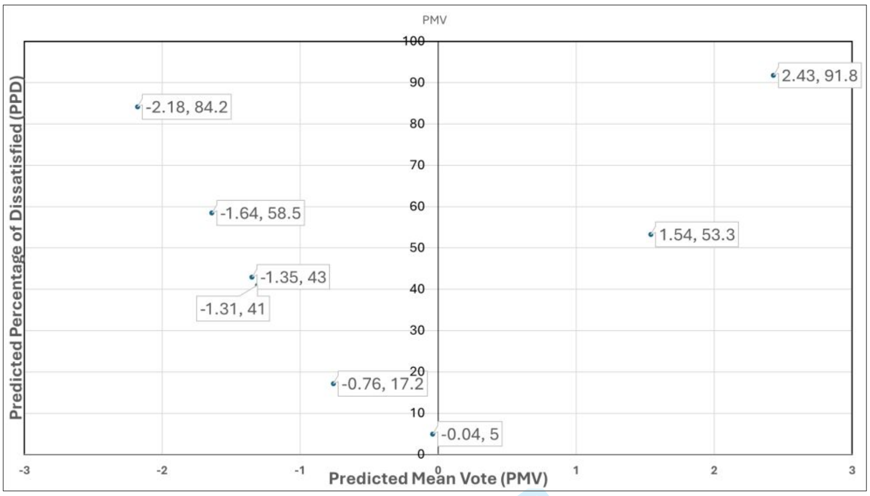


Figure 5 PMV and PPD of employees in offices during Summer and Winter

The DPI, PSDA and PCS offices did not comply with the LEED due to high and low PMV during summer and winter respectively. Based on the typing as metabolic activity and light, heavy clothing insulation in summer and winter, the highest SET was experienced in winter than in summer and an average person felt warm in winter and cool in summer within these offices. The power consumption of the measured offices was calculated based on the ventilation modes, operating devices, number of employees and envelope design. In addition to office equipment, the power consumption in DPI, GH and PCS offices was higher during winter than in summer due to the electric heater *(Figure 20)*.

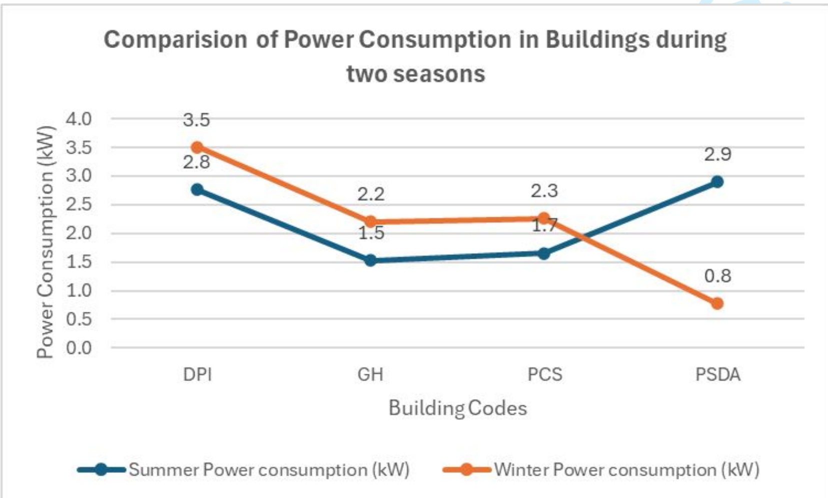


Figure 6 Power Consumption in Offices during Summer and Winter

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

Conclusion and Future Directions

During summer and winter, the results of environmental monitoring of temperature, humidity, $PM_{2.5}$, CO_2 and employees' subjective assessment for IAQ and thermal comfort showed that the sampled offices in Lahore did not meet the ASHRAE, WHO and EPA standards. The concentrations of CO_2 in summer and $PM_{2.5}$ during winter were well above the recommended standards, reaffirmed by employees' dissatisfaction. The adaptive comfort standards for naturally ventilated offices provided comfort temperature at 35°C. Various building controls of windows, doors, wind chimneys and ventilators can help employees adapt to higher thermal conditions. Filtration and ventilation through wind catchers is a solution for offices with 80-90% acceptability of IAQ and thermal comfort as recommended by ASHRAE standards. The passive measures of wind chimneys, ventilators, street-level windows, courtyards and verandas were not used to ventilate offices. The wind chimneys were designed to be used with other passive measures but in existing offices GH and PCS, they were the source of pollution. Most wind chimneys, skylights and windows were closed which did not provide the crossflow of wind ventilation. The thermal shifts in air-conditioned and non-air-conditioned environments of offices, incorrect use of passive measures and existing filtration choices were the barriers to thermal comfort and IAQ. Employees have reported the acceptability of the modern wind catcher, so the Computational Fluid Dynamic analysis is suggested. The existing wind catcher design and green filtration techniques can be combined for experimental purposes to improve thermal comfort and IAQ for Lahore, Pakistan.

Funding: "This research work was supported by Inisiatif Putra Siswazah grant ID No.: GP-IPS/2022/9736900 from Universiti Putra Malaysia Serdang Campus.

Statements of authors' contribution

All authors equally contributed to the preparation and finalization of the manuscript.

Acknowledgment

The authors acknowledge the help and support of **Mr. Anwar & Ms. Farah Samia** from Governor House, **Ms. Syeda Shameem Jaferi** from the Punjab Civil Secretariat, **Mr. Haroon** from Punjab Skill Development Authority, and **Mr. Salman** from the Directorate of Public Instruction.

Declaration of conflicting interests

The Authors declare that 'there is no conflict of interest'.

References

1. Faiz Y, Tufail M, Javed MT, Chaudhry, M. M, Naila-S. Road dust pollution of Cd, Cu, Ni, Pb and Zn along Islamabad Expressway, Pakistan. *Microchemical Journal* 2009; 92: 186–192. DOI: 10.1016/j.microc.2009.03.009.
2. Anjum MS, Ali SM, Imad-ud-din M, Subhani MA, Anwar MN, Nizami AS, Ashraf U, Khokhar MF. An Emerged Challenge of Air Pollution and Ever-Increasing Particulate Matter in Pakistan; A Critical Review. *J Hazard Mater* 2021; 402: 1-15. DOI: 10.1016/j.jhazmat.2020.123943.

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

3. Haider R, Yasar A, Tabinda AB, Basharat A. Assessment of Street air pollution through OSPM model in Lahore, Pakistan. *Environmental Engineering & Management Journal (EEMJ)* 2021; 20: 73-80.

4. Pakistan Bureau of Statistics. Compendium on Environment Statistics of Pakistan - 2004. https://www.pbs.gov.pk/publication/compendium-environment-statistics-pakistan-2004 (2004, accessed 26 April 2022).

5. WHO. WHO *global air quality guidelines*, https://www.who.int/publications/i/item/9789240034228 (2021) (2021, accessed 12 January 2022).

6. Colbeck I, Nasir ZA, Ali Z, Safdar S. Indoor air quality in Lahore, Pakistan. In EAC 2013: Proceedings of the European Aerosol Conference, Prague, Czech Republic, 1st - 6th September 2013; UNESCO Czech Heritage, 2013.

7. Colbeck I, Nasir ZA, Ali Z. The state of ambient air quality in Pakistan — a review. *Environmental Science and Pollution Research* 2009; 17: 49–63. DOI: 10.1007/s11356-009-0217-2

8. World Bank. *Pakistan Strategic Country Environmental Assessment*, https://documents1.worldbank.org/curated/en/132221468087836074/pdf/3694610vol011PK.pdf (2006, accessed 10 January 2025).

9. United Nation. *UN-Habitat Strategic Plan 2020-2023*. Report no. 23792027. DOI: 10.1109/NAECON46414.2019.9058320. https://unhabitat.org/sites/default/files/2021/10/strategic_plan_2020-2023-overview.pdf (2020, accessed 21 November 2021).

10. Mannan M, Al-Ghamdi SG. Indoor air quality in buildings: A comprehensive review on the factors influencing air pollution in residential and commercial structure. *Int J Environ Res Public Health* 2021; 18: 1–24. DOI: 10.3390/ijerph18063276

11. Mazhar N, Brown RD, Kenny N, Lenzholzer S. Thermal comfort of outdoor spaces in Lahore, Pakistan: Lessons for bioclimatic urban design in the context of global climate change. *Landsc Urban Plan* 2015; 138: 110–117. DOI: 10.1016/J.LANDURBPLAN.2015.02.007

12. Colbeck I, Nasir ZA, Hasnain S, Sultan S. Indoor Air Quality at Rural and Urban Sites in Pakistan. *Water, Air, & Soil Pollution: Focus* 2008; 8: 61–69. DOI: 10.1007/s11267-007-9139-5

13. Hamers L. Air pollution is triggering diabetes in 3.2 million people each year | Science News. *New study quantifies the link between smoggy air and diabetes*, https://www.sciencenews.org/article/air-pollution-triggering-diabetes-in-millions-each-year?fbclid=IwAR22L92xBmX_q6Baiv7E8shO7JKwx46pnsFhfhPbaqrBdMkx6u_bUA5Xt6A&fs=e&s=cl (2018, accessed 12 July 2022).

14. Health Effects Institute. *State of Global Air 2019 - A Special Report on Global Exposure to Air Pollution and its Disease Burden*. Boston, MA: Health Effects Institute. DOI: 2578-6873. ISSN 2578 – 6873. 2019.

15. Naseem I, Sikander A, Hameed N, Khan R. Factors Affecting Employees' Performance: Evidence from Pakistan. Science Series Data Report 2012; 4: 141–174.

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

16. Carrer P, Wolkoff P. Assessment of indoor air quality problems in office-like environments: Role of occupational health services. *Int J Environ Res Public Health 2018 Apr 12*; 15(4):741. DOI: 10.3390/ijerph15040741.

17. Wolkoff P. Indoor air humidity, air quality, and health – An overview. *Int J Hyg Environ Health* 2018; 221: 376–390. DOI: 10.1016/j.ijheh.2018.01.015

18. Mujan I, Anđelković AS, Munćan V, Kljajić M, Ružić D. Influence of indoor environmental quality on human health and productivity - A review. *J Clean Prod* 2019; 217: 646–657. DOI: 10.1016/j.jclepro.2019.01.307

19. Qayyum S, Tariq S, Younas F. Sick building syndrome and job performance in women factory workers. *Journal of Postgraduate Medical Institute* 2020; 34: 22–28.

20. Lodhi K. *An investigation into HVAC option for an office building in Pakistan*. PhD Thesis, University of London, University College London (United Kingdom), London, 2005. DOI: U594119.

21. Noureen H. *Solutions for Energy Crisis in Pakistan*. Islamabad, https://www.csspmspk.com/wp-content/uploads/wpforo/default_attachments/1624592224-Energy-Crisis-in-Pakistan-complete-document.pdf#page=244 (2014) (2014, accessed 29 April 2022).

22. Murtyas S, Qian R, Matsuo T, Tuck Ng W, Zaki Sheikh A, Hagishima A. Thermal comfort in a two-storey Malaysian terrace house: Are passive cooling methods sufficient in present and future climates? *Journal of Building Engineering* 2024; 96: 110412. DOI: 10.1016/J.JOBE.2024.110412

23. Humphreys RMA. An adaptive approach to the thermal comfort of office workers in North West Pakistan. *Renew Energy* 1994; 5: 985–992. DOI: 10.1016/0960-1481(94)90121-X

24. Haroon MU, Ozarisoy B, Altan H. Factors Affecting the Indoor Air Quality and Occupants' Thermal Comfort in Urban Agglomeration Regions in the Hot and Humid Climate of Pakistan. *Sustainability 2024, 16* : 7869. DOI: 10.3390/su16177869

25. Zahid M, Khan R. Carbon dioxide monitoring in office buildings: The case-study of Sui Northern Gas Pipelines Limited in Lahore. IEEE SEM~~,~~ 2019; 7: 109–125.

26. Jomehzadeh F, Nejat P, Calautit JK, Yusof MBM, Zaki SA, Hughes BR, Yazid, Muhammad NAWM. A review on windcatcher for passive cooling and natural ventilation in buildings, Part 1: Indoor air quality and thermal comfort assessment. *Renewable and Sustainable Energy Reviews* 2017; 70: 736–756. DOI: 10.1016/J.RSER.2016.11.254.

27. Tavakolinia F. *Wind-Chimney Integrating the Principles of a Wind-Catcher and a Solar-Chimney to Provide Natural Ventilation*. MS Architecture Thesis, California Polytechnic State University, San Luis Obispo, December 2011.

28. Khalid A, Dahlan ND. Wind Catcher: A Lost Architectural Heritage with Timeless Passive Attributes. In: Hmood ProfKF (ed) *Conservation of Urban and Architectural Heritage - Past, Present, Future*. Rijeka: IntechOpen, pp. 163–185. DOI: 10.5772/intechopen.109974

29. Monodraught UK. Monodraught, https://www.monodraught.com/ (2020, accessed 4 December 2022).

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

30. Monodraught. Marketing Team Monodraught - YouTube. *WINDCATCHER® X-air Natural Ventilation*, https://www.youtube.com/channel/UCu0reh-oOGg7GOZ4fKmMRtQ (2010, accessed 8 December 2022).

31. IES. *Monodraught Performance Components User Guide v1.0*. Nottingham UK, Integrated Environmental Solutions, 2012.

32. Jafari S, Kalantar V. Numerical simulation of natural ventilation with passive cooling by diagonal solar chimneys and windcatcher and water spray system in a hot and dry climate. *Energy Build 2022 February; 256: 111714*. DOI: 10.1016/j.enbuild.2021.111714.

33. Moosavi L, Zandi M, Bidi M, Behroozizade E, Kazemi I. New design for solar chimney with integrated windcatcher for space cooling and ventilation. *Build Environ* 2020; 181: 106785. DOI: 10.1016/j.buildenv.2020.106785

34. ANSI/ASHRAE 55-2023. Thermal Environmental Conditions for Human Occupancy. Atlanta: The American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2023. https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy (accessed 21 June 2024).

35. Luo~~,~~ M.~~ (2023)~~. Adaptive Thermal Comfort. In: Wang~~,~~ F~~.~~, Yang~~,~~ B~~.~~, Deng~~,~~ Q~~.~~, Luo~~,~~ M. (eds) Personal Comfort Systems for Improving Indoor Thermal Comfort and Air Quality. Indoor Environment and Sustainable Building. Springer, Singapore, 2023. https://doi.org/10.1007/978-981-99-0718-2_2

36. CIBSE. CIBSE Guides. https://www.cibse.org/knowledge-research/knowledge-resources/engineering-guidance/cibse-guides, 2012 (2012, accessed 21 June 2024).

37. IQAir Staff Writers. New EPA annual $PM_{2.5}$ air quality standards expected to save lives. https://www.iqair.com/us/newsroom/new-epa-annual-PM2.5-air-quality-standards-expected-save-lives (2024, accessed 20 June 2024).

38. Wladimir Köppen RG. Köppen-Geiger Climate Classification. *World Maps of Köppen-Geiger climate classification*, https://koeppen-geiger.vu-wien.ac.at/ (2011, accessed 7 October 2024).

39. Betti G, Tartarini F, Nguyen C, Schiavon S. CBE Clima Tool: A free and open-source web application for climate analysis tailored to sustainable building design. *Build Simul* 2024; 17: 493–508.

40. Huizenga C, Abbaszadeh S, Zagreus L, Arens, E. Air quality and thermal comfort in office buildings: Results of a large indoor environmental quality survey. Proceedings of *HB 2006 - Healthy Buildings: Creating a Healthy Indoor Environment for People.* Lisbon, 4-8 June 2006; Vol 3: pp393–397.

41. Allam H. *Retrofitting adaptive comfort strategies into conventionally air conditioned commercial buildings*. Master Thesis of Philosophy, The University of Sydney, Sydney, 2014.

42. Merabtine A, Maalouf C, Al Waheed Hawila A, Martaj N, Polidori G. Building energy audit, thermal comfort, and IAQ assessment of a school building: A case study. *Build Environ* 2018; 145: 62–76.

43. Hamzah B, Gou Z, Mulyadi R, Amin S. Thermal comfort analyses of secondary school students in the tropics. *Buildings* 2018; 8: 1–19.

44. Vaitheeswaran K, Anush P. A Strategically Approach To Improve Thermal Comfort in Education Institution. *Ijair* 2015; 4: 135–137.

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

45. Newsham GR, Tiller DK. Field Study of Office Thermal Comfort Using Questionnaire Software. IRC Internal Report 708, NRC Publications Archive (NPArC), November 1995. DOI: 10.4224/20375335.

46. Alzaid A, Kolokotroni M, Awbi H. Thermal comfort assessment based on measurement and questionnaire surveys in a large mechanically Ventilated space. In: *Network for Comfort and Energy use in Building, Proceedings of 10th Windsor Conference: Rethinking Comfort*. Cumberland Lodge, Windsor UK, 12th – 15th April 2018, pp. 836–850.

47. Tan YQ, Rashid SKA, Pan WC, Chen YC, Yu, Liya E, Seow WJ. Association between microenvironment air quality and cardiovascular health outcomes. *Science of The Total Environment* 2020; 753: 1-10. DOI: 10.1016/j.scitotenv.2020.141904.

48. Norback D, Edling C. Environmental, occupational, and personal factors related to the prevalence of sick building syndrome in the general population. *Br J Ind Med* 1991; 48: 451–462. DOI: 10.1136/oem.48.7.451.

49. Zhang L, Wei D, Hou Y, Du J, Liu Z, Zhang G, Shi L. Outdoor thermal comfort of urban park-A case study. *Sustainability (Switzerland)* 2020; 12: 1–23. DOI: 10.3390/su12051961.

50. NEECA. *Energy Conservation Building Code-2023*, https://www.neeca.gov.pk/SiteImage/Downloads/ecbc23.pdf (2023, accessed 13 October 2024).

51. ISO 7730. International Standard ISO 7730. (*Will be replaced by ISO/DIS 7730d mean vote* 2005); International Organization for Standardization, Geneva, 2005: 52.

52. ANSI/ASHRAE Standard 62.1-2016. Ventilation for acceptable Indoor air Quality. ~~ASHRAE 62.1,~~ Atlanta, USA, 2016.

53. USA-EPA. An Office Building Occupant's Guide to Indoor Air Quality. *An Office Building Occupant's Guide to Indoor Air Quality*. https://www.epa.gov/indoor-air-quality-iaq/office-building-occupants-guide-indoor-air-quality (2024, accessed 16 July 2024).

54. Lim Q Y. *Effectiveness of Air Purifying Paints for Improving Indoor Air Quality in Offices*. The Libraries of ASEAN University Network. National University of Singapore, Singapore, 2022. ScholarBank@NUS Repository.

55. Liu Y, Zhou B, Wang J, Zhao B. Health benefits and cost of using air purifiers to reduce exposure to ambient fine particulate pollution in China. *J Hazard Mater 2021*; 414: 125540. DOI: 10.1016/j.jhazmat.2021.125540.

56. Niza IL, de Souza MP, da Luz IM, Broday EE. Sick building syndrome and its impacts on health, well-being and productivity: A systematic literature review. Indoor and Built Environment. 2024;33(2):218-236. doi:10.1177/1420326X231191079

57. Gül H, Işsever H, Ayraz Ö, Güngör G. Occupational and Environmental Risk Factors for the Sick Building Syndrome in Modern . doi:10.1177/Offices in Istanbul: A Cross-Sectional Study. Indoor and Built Environment~~.~~ 2007;16(1):47-54. ~~1420326X06074502~~

58. Fu X, Norbäck D, Yuan Q, Li Y, Zhu X, Hashim JH, Hashim Z, Ali F. Association between indoor microbiome exposure and sick building syndrome (SBS) in junior high schools of Johor Bahru, Malaysia. *Science of the Total Environment 2021*; 753:141904. DOI: 10.1016/j.scitotenv.2020.141904.

Cite this article:
Khalid A, Dahlan ND, Bin Abas MF, Bin Ahmad KA, Shahidan MF. The impact of wind catchers on thermal comfort and indoor air quality: An analysis of subtropical climate for summer and winter. Indoor and Built Environment. 2025;34(4):838-867. doi: 10.1177/1420326X251323242

59. Rostron J. Sick building syndrome: A review of causes, consequences and remedies. *Journal of Retail & Leisure Property* 2008; 7: 291–303. DOI: 10.1057/rlp.2008.20.

60. Salari M, Tabatabaei FS, Fouladi-Fard R, Mohammadbeigi A, Nadali A, Fahiminia M, Fiore M. Influence of heating systems on indoor air quality and sick building syndrome (a case study in Qom, Iran). *International Journal of Ventilation* 2023; 22: 257–272. DOI: 10.1080/14733315.2022.2068250

61. Tsai DH, Lin JS, Chan CC. Office Workers' Sick Building Syndrome and Indoor Carbon Dioxide Concentrations. *J Occup Environ Hyg* 2012; 9: 345–351. DOI: 10.1080/15459624.2012.675291.

62. Foruzanmehr A. The wind-catcher: Users perception of a vernacular passive cooling system. *Archit Sci Rev* 2012; 55: 250–258. DOI: 10.1080/00038628.2012.722070.

63. Mohamed M, Mohammed MFM. Investigating the environmental performance of the wind catcher in Jeddah. *WIT Transactions on the Built Environment* 2018; 177: 15–26. DOI: 10.2495/IHA180021.

64. Yan T, Jin H, Jin Y. The mediating role of emotion in the effects of landscape elements on thermal comfort: A laboratory study. *Build Environ 2023*; 233: 110130. ~~Epub ahead of print 1 April 2023.~~ DOI: 10.1016/j.buildenv.2023.110130.

65. Abbas Elmualim HBA. Post-occupancy monitoring of windcatchers for summer ventilation in the UK. In: Proceedings of the 7th International Conference of Healthy Buildings 2003, National University of Singapore. Singapore, 7 – 11th December 2003. ~~*Healthy Building Conference*,~~ https://www.emerald.com/insight/content/doi/10.1108/02632770310507980/full/html (2003, accessed 7 July 2024).

66. Tartarini F, Schiavon S, Cheung T, Hoyt T. CBE Thermal Comfort Tool: Online tool for thermal comfort calculations and visualizations. SoftwareX 2020; 12: 100563. DOI: 10.1016/J.SOFTX.2020.100563.