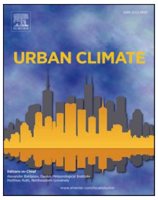
Urban Climate 49 (2023) 101466

Contents lists available at ScienceDirect

Urban Climate

journal homepage: www.elsevier.com/locate/uclim



The effects of passive design on indoor thermal comfort and energy savings for residential buildings in hot climates: A systematic review

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ARTICLE INFO

Keywords:
Passive design
Residential building
Energy saving
Indoor thermal comfort
Hot climates

ABSTRACT

In this study, a systematic review and meta-analysis were conducted to identify, categorize, and investigate the effectiveness of passive cooling strategies (PCSs) for residential buildings. Forty-two studies published between 2000 and 2021 were reviewed; they examined the effects of PCSs on indoor temperature decrease, cooling load reduction, energy savings, and thermal comfort hour extension. In total, 30 passive strategies were identified and classified into three categories: design approach, building envelope, and passive cooling system. The review found that using various passive strategies can achieve, on average, (i) an indoor temperature decrease of 2.2 °C, (ii) a cooling load reduction of 31%, (iii) energy savings of 29%, and (v) a thermal comfort hour extension of 23%. Moreover, the five most effective passive strategies were identified as well as the differences between hot and dry climates and hot and humid climates.

1. Introduction

Globally, passive design strategies were applied in traditional buildings in hot climates to provide satisfactory indoor thermal environments long before the invention of modern mechanical cooling systems (Mohammadi et al., 2018; Salameh and Touqan, 2022; Zune et al., 2020). Passive design strategies have been identified by researchers as preferable for constructing low-energy buildings due to their potential to reduce the cooling and heating load demand (Chen and Yang, 2017; Bhamare et al., 2019; Campaniço et al., 2014). Despite PCSs being available worldwide, there has been growing dependence on active (mechanical) air-conditioning systems (Cox et al., 2010; Lundgren-Kownacki et al., 2018). Active air-conditioning, as opposed to building designs that keep indoor temperatures down, is a relatively recent phenomenon. The first modern electrical air-conditioning unit was only invented at the beginning of the 20th century, and widespread adoption was initiated in the United States in the 1950s (EIA, 2018). Now, air-conditioned homes are common in the United States, with around 90% of American households having some type of air-conditioning system according to 2015 Residential Energy Consumption Survey data (EIA, 2018), while fewer than 10% of households in Europe are air-conditioned

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https://doi.org/10.1016/j.uclim.2023.101466
Received 18 December 2022; Received in revised form 3 February 2023; Accepted 21 February 2023

(IEA, 2018), and the adoption of air-conditioning in developing countries, like China and India, is rapidly increasing. Climate change is normalizing extreme heat across the globe (Fraser et al., 2018), with the recent heat wave in 2022 as an example (Kearl and Vogel, 2023). More and more frequent heat events will continue to increase the demand and dependency on air-conditioning. Global air-conditioning system sales more than tripled between 1990 and 2016, and the growth is likely to continue (IEA, 2018).

There are three major problems associated with over-dependency on air-conditioning systems. The first is increased energy consumption, with cooling devices (air-conditioning and electrical fans) accounting for about 20% of global electricity consumption (IEA, 2018), and air-conditioning accounting for 8% of the total energy use of US residential buildings (EIA, 2023). With the increasing adoption of air-conditioning systems, global energy use will likely increase as well as the carbon emissions from energy consumption. The second problem is the stress incurred by the power grid and vulnerability to power outages—due to increased energy demand from air-conditioning—particularly during heatwaves in developing countries when the original power grid capacity becomes over-stretched. The third problem is environmental inequality. Increasingly extreme weather events fueled by climate change, coupled with inequalities in countries' disaster response systems, have disproportionate impacts on low-income families and vulnerable populations. Among weather events, heatwaves are the leading cause of death in many countries, including developed nations such as the US and Australia, and cooler climate regions, such as Northern Europe. Mortality figures are typically dominated by victims from vulnerable populations, such as the elderly ($\geq$ 65 years old), young children, and pregnant women; persons suffering from diabetes, obesity, hypertension, respiratory disease, or mental illness; and those from low-income households or who are socially isolated (Kravchenko et al., 2013; Zuo et al., 2015).

To adapt to more frequent and intensified heatwaves caused by climate change while minimizing energy consumption increase and accounting for potential power outages, the application of passive design strategies is critical to prepare existing and new residential buildings. Passive strategies do not all result in energy use during the operation, and most passive strategies are low cost or at no cost, which are practical techniques for use by low-income communities in hot climates. However, because of over-dependency on mechanical air-conditioning systems in developed countries, such as the United States, knowledge of applying passive design strategies has gradually diminished. In some areas of the world, people still apply passive strategies inherited from their ancestors, but passive strategies are generally becoming obsolete due to a lack of guidance and requirements in building codes and regulations. For example, Akande (2010) indicated that apartment design in Nigeria is not generally responsive to the local climate; therefore, dependence on electrical ventilation is common in all apartments. Further, frequent power outages, sometimes over six hours a day, have created tremendous heat stress in urban dwellers' lives.

Moreover, although passive design strategies have been accepted as a rule of thumb or ancient wisdom, there is a limited understanding of the types of strategies available and their associated quantifiable thermal improvement or energy-saving benefits. The omission of applying passive design is partially due to insufficient evidence of the effectiveness of passive strategies, especially for the thermal comfort. There are a few reviewed published on the energy saving potential of applying passive cooling strategies. For example, Friess & Rakhshan, (2017) reviewed over twenty studies conducted in United Arab Emirates (UAE), they concluded that the building envelope passive strategies (e.g., window-to-wall ratio) have the potential to significantly reduce the overall energy use in UAE. Another review was conducted for Malaysia on the effectiveness of building envelope design on energy consumption of high-rise buildings. Moreover, most existing review papers focused on specific climate regions defined by geographical boundaries because applicable passive cooling strategies vary significantly per climatic conditions (i.e., hot and humid vs hot and dry). On the same line, the passive strategies used in cold climate are often not applicable to hot climatic condition. To date, there is limited global review looking into all hot climate and providing findings that can generalized. A thorough understanding of passive cooling strategies (PCSs) for residential buildings in hot climates is critical for providing empirical evidence and guidelines for applying passive cooling techniques in future projects.

The goal of this paper is to review recent progress in assessing and measuring passive cooling effects related to indoor heat exposure mitigation through reducing the indoor temperature and cooling load demand. The effects can also be measured in energy savings and comfort hour extension. More specifically, in this systematic review and meta-analysis, the author aims to provide evidence to answer the following research questions:

1. What PCSs have been used in residential buildings in different hot climates?
2. What measurements have been used to quantify the benefits of PCSs?
3. What evidence has been found of applying passive strategies in a residential context?

2. Method and materials

2.1. *Defining hot climate*

Since this review focused on passive strategies' effectives on energy saving and comfort improvement, therefore, the definition provided by U.S Department of Energy was adopted. Hot climate includes hot-humid and hot-dry conditions. A hot-humid climate is defined as a region that receives more than 50 cm of annual precipitation and where either 19.5 °C or higher wet bulb temperature for 3000 or more hours during the warmest 6 consecutive months of the year, or 23 °C or higher wet bulb temperature for 1500 or more hours during the warmest 6 consecutive months (Department of Energy, 2022). A hot-dry climate is defined as a region that receive less than 50 cm of annual precipitation and where the monthly average outdoor temperature remain above 7 °C through the year (Department of Energy, 2022).

2.2. Defining passive design

Passive design differs from the Passive House standard (*Passivhaus* in German) and passive solar design. The Passive House standard is an energy-efficient design guideline and rating system that originated in Germany with goals of reducing energy use while providing a healthy and thermal comfortable indoor environment. Its design approach includes both active and passive design strategies. According to the U.S. Department of Energy's definition, passive solar design takes advantage of a building's site, climate, and materials to minimize energy use, with a focus on solar energy. This study focuses on passive design strategies as opposed to active design strategies. Active systems use purchased or imported energy (e.g., electricity and gas) to create an artificial indoor thermal environment through mechanical ventilation and air-conditioning, while passive systems use ambient energy sources (e.g., sun and wind) to create a thermally comfortable indoor environment. Generally, passive systems do not consume energy during the operation and are low technology and low cost. While the definition of passive design remains ambiguous, the above-mentioned definition is used for this systematic review.

2.3. Literature review

A systematic review approach was used to extract information published in the last several decades on the effectiveness of passive design strategies in buildings, with a focus on residential buildings. This approach was initially used in the field of medicine (Askie and Offringa, 2015); now it is common in other disciplines, including construction management (Ayodele et al., 2020) and the built environment (Pomponi et al., 2016). Compared to a conventional literature review, a systematic review uses a systematic and documented process for screening, selecting, and synthesizing the literature for inclusion in the review (Askie and Offringa, 2015). It is valuable in providing a reliable evaluation and synergy of previous literature from which researchers can draw conclusions, identify knowledge gaps, and make informative decisions (Rañeses et al., 2021). A systematic review uses a methodical scheme, from identifying the issue and determining the question to forming the review protocol, including predefined eligibility criteria for studies. Its purpose is to minimize bias and provide more reliable findings (Askie and Offringa, 2015).

As shown in Fig. 1, a protocol for this study was developed based on the preferred reporting items for systematic review and meta-analysis (PRISMA) protocol guidelines (Shamseer et al., 2015). It comprises several stages: (a) identify the publications, (b) screen the publications, (c) assess the eligibility of the publications based on predefined criteria, and (4) conduct the synthesis and meta-analysis.

The databases Web of Science, ProQuest, and PubMed were used. The following search terms and similar words were used in the initial identification of publications:

- Passive strategies: Passive cooling, Passive design, Hot climate sensitive, Natural ventilation, Evaporation cooling, Thermal cooling, Building orientation
- Building: Residential building, House

The publications included were selected based on the following criteria: (i) the study addressed indoor thermal comfort and passive strategies as the main research topic; (ii) the study relied on empirical data (on-site measurement or simulation) to draw a conclusion;

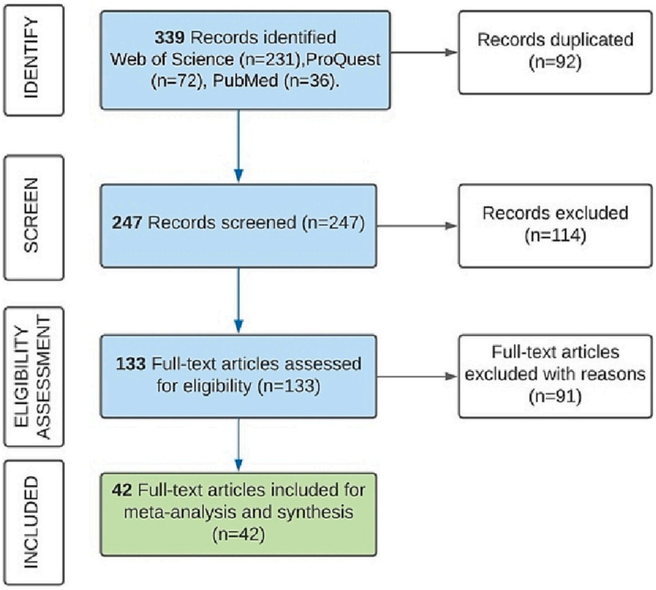

Fig. 1. Flowchart of the review process (PRISMA flow diagram).

(iii) the study specified passive design variables and their measurement unit, with quantified effectiveness either measured in temperature decrease or energy savings; and (iv) the study focused on low-cost passive design (double skin façade was excluded).

As illustrated in Fig. 1, initially, a total of 339 publications were identified from Web of Science ($n = 231$), ProQuest ($n = 72$), and PubMed ($n = 36$). The included disciplines and fields were epidemiology, environmental health, environmental science, construction, engineering, and architecture. Among the three data sets, 92 publications overlapped, resulting in 247 identified articles. To narrow down the publications, we conducted the initial screen by reading through the abstract of all founded articles. After the abstract screen, 133 publications were selected for full-text eligibility assessment using the criteria identified above. After the full-text assessment, 42 articles were included for meta-analysis, synthesis, and conclusion building.

2.4. Meta-analysis

Unlike a systematic review, a meta-analysis is a statistical synthesis of the results of previous studies that addressed a related hypothesis in a similar way (Ganeshkumar and Gopalakrishnan, 2013). Simply put, a meta-analysis is a statistical procedure for combining data from multiple studies. Individual studies are usually small and may not directly lead to significant results but may contribute collectively to an outcome or a new body of knowledge. In the building and construction field, meta-analysis is used to study quantitative methodologies of sustainability in construction (Adolpho Guido et al., 2020) and investigate the embodied energy and carbon of buildings (Minunno et al., 2021). However, the use of meta-analysis is limited for sustainable building and passive design. To the authors' knowledge (based on the literature review), no meta-analysis has been conducted yet on the effectiveness of passive design on indoor temperature control and energy savings.

3. Findings: passive design strategies in hot climates

A total of 42 studies were included in the final full-text review and meta-analysis, and 30 PCSs were included in the review. The PCSs can be grouped into three categories: design approach (DA), building envelope (BE), and cooling system (CS), as listed in supplement document column six of Table 1.The passive strategies included in the study can be divided into three categories: load reduction, passive solar heating, and passive cooling.

This paper focuses on load reduction and passive cooling. Compared to passive heating, passive cooling is much more dependent on climate. Therefore, the PCSs for a hot and dry climate can differ from those for a hot and humid climate. The strategies for load reduction can be categorized into the overall design approach and building envelope design. There are 30 PCSs included in this review as listed in Table 1. In the following sections, explanations of primary passive strategies included in this study will be provided. The primary passive strategies are those that were studied by more than three publications. The selected PCSs have been grouped into three

Table 1
Passive cooling strategies.

Passive Cooling Strategy	Passive Category	Description	Climatic Condition
PCS 1	DA	Orientation	All
PCS 2	DA	Geometry/form/height	All
PCS 3	DA	Courtyard	All
PCS 4	DA	Roof shape (dome, vault)	All
PCS 5	DA	Sloped roof	Hot and dry
PCS 6	DA	Window-to-ground ratio	All
PCS 7	DA	Patio	Hot and dry
PCS 8	DA	Space utilization	All
PCS 9	BE	Roof property	All
PCS 10	BE	Exterior wall property	All
PCS 11	BE	Interior wall property	All
PCS 12	BE	Glazing/window	All
PCS 13	BE	Replace single glazing with double glazing	All
PCS 14	BE	Overhang projection factor	All
PCS 15	BE	Horizontal shading	All
PCS 16	BE	Vertical shading	All
PCS 17	BE	Window-to-wall ratio	All
PCS 18	BE	Green roof	Hot and dry
PCS 19	BE	Floor/ground thermal property	All
PCS 20	BE	Cool roof	All
PCS 21	BE	Color (or paint) of exterior wall	All
PCS 22	CS	Passive evaporative cooling	All
PCS 23	CS	Natural ventilation	All
PCS 24	CS	Night ventilation	All
PCS 25	CS	Solar chimney	All
PCS 26	CS	Wind catcher	All
PCS 27	CS	Ground-coupling cooling (earth pipe cooling system)	Hot and dry
PCS 28	CS	Water-to-air heat exchanger	Hot and humid
PCS 29	CS	Hydraulic-driven ventilation device	Hot and humid
PCS 30	CS	Earth sheltering (semi-basement)	Hot and humid

passive strategy categories: design approach (DA), building envelope (BE), and cooling system (CS).

3.1. Overall design approach (DA)

3.1.1. Building orientation and courtyard

Building orientation (PCS1) has been shown to be critical in reducing the load, both for cooling and heating. Orienting the shorter side of the building toward the east and west can minimize summer cooling loads. In hot climates, outdoor spaces should be situated on a shaded side and be in the path of breezes as much as possible. Semi-outdoor spaces, such as courtyards (PCS3), have been a passive strategy used in hot and dry climates and hot and humid climates (Kubota et al., 2017; Manioğlu and Oral, 2015). This type of space introduces two benefits to create a thermally comfortable environment. First, openings can be concentrated toward the courtyard, under the shade. Consequently, direct solar gain can be avoided, reducing the cooling load (Al-Masri and Abu-Hijleh, 2012). The studies included in this review demonstrate the significant impact of a courtyard. For example, according to Xu et al. (2018), the peak cooling load can be reduced by 12.4% and the total cooling load by 25.1%. Second, courtyards are often used to enhance convective cooling through ventilation. When integrated with water features, a courtyard can be used for passive evaporative cooling (PCS22). When used together with a wind catcher or wind tower, a courtyard can enhance stack ventilation. For example, Kaihoul et al. (2021) demonstrated the effectiveness of a courtyard combined with a wind catcher (PCS26) to keep the indoor temperature between 30.1 °C and 35.4 °C, with an outdoor temperature of 47 °C.

3.1.2. Building form and roof shape

A building may be thought of as forming a "footprint" on the land (Bradshaw, 2010). Depending on building orientation on-site and exposure to solar radiation, the building's form and shape (PCS2) can either dissipate or retain heat. Various measures have been used by researchers to describe a building's form and shapes, such as the building's height and length. However, attempts to quantify the optimal form of a building have produced unclear results. For example, St. Clair and Hyde (2009) concluded that if a building's floor depth is over 15 m, the effectiveness of natural ventilation will decrease. Meanwhile, Kannan (1992) claimed there is no definite correlation between building form (height) and energy use. However, two commonly used ratios indicated a close correlation between building energy use and thermal comfort: the aspect ratio—the ratio of a building's length to its width (Bradshaw, 2010), and the height-to-depth ratio—the ratio of a building's floor depth to its height. Clements-Croome (2005) recommended proper ventilation that the height-to-depth ratio be 2:1 for single-corridor buildings and 2.5:1 for double-corridor buildings. Regarding the aspect ratio, the earliest study by Olgyay, suggested the optimal shape for a skin-load dominated building in any climate be a rectangular form, with the elongated side along the east-west axis (Olgyay, 2015). Residential buildings and small-scale commercial buildings are skin-load dominated buildings, where the energy use is primarily determined by the influence of the exterior climate on a building's envelope, or "skin" (Fosdick and Homes, 2008). According to Olgyay, (2015) an acceptable aspect ratio for buildings in a hot and humid climate ranges between 1:1.17 and 1:3, where 1:1.17 is optimal.

In addition to the overall building shape, the roof shape (PCS4) is another study focus because the most direct solar heat gain is through the roof. The shape and slope of the roof has been studied by various researchers. For example, 37 roof design probabilities, alternating roof shape and materials, were studied by Dabaieh et al. (2015), with findings indicating comfort hours can be extended by 53%. Some traditional low-tech roof designs have attracted researchers' attention. For example, massive domed roofs or vault roofs have been used successfully in hot and dry climates. Besides the thermal benefit of their mass, their form yields two different benefits. During the daytime, only a small area of the domed roof captures direct solar heat; at nighttime, almost the full hemisphere can emit the stored heat to the cool night sky. Therefore, radiant heating is minimized while radiant cooling is maximized.

3.1.3. Window-to-wall ratio

Solar heat transmission through the building envelope, especially windows, significantly contributes to the cooling load demand in residential buildings. The window-to-wall ratio (WWR) (PCS17) determines the amount of incident solar radiation that is admitted indoors (Mirrahimi et al., 2016). Despite the research and practice community's consensus on the importance of the WWR, its effectiveness of the WWR is still debatable. For example, Liping and Hien (2007) claimed ventilation and indoor thermal comfort can be enhanced by 13% with a WWR increase, from 12% to 24%. However, other studies showed opposite results: Ralegaonkar and Gupta (2010) studied four WWRs—20%, 40%, 60%, and 80%—in Turkey and found that energy use increased when the WWR increased. Besides the WWR, the window-to-ground ratio (PCS6) has also been used to measure the appropriate size of a window, but it was only found in one study.

3.2. Building envelope (BE)

The building envelope includes the exterior walls and roof and their associated building components, such as shading devices.

3.2.1. Exterior wall thermal property and reflectivity

The external walls are an important component of the building envelope; they allow for passive control of indoor thermal conditions through the management of external heat transfer (Ralegaonkar and Gupta, 2010). To provide a stable thermally comfortable indoor environment (temperature and humidity) despite the fluctuation of outdoor conditions, the exterior walls need to have a high degree of thermal inertia and thermal resistance. Thermal inertia is the measure of how well building materials and components can absorb solar heat without increasing their temperature (Avendaño-Vera et al., 2020). Thermal resistance is the measure of how well external walls can resist heat flow (Desogus et al., 2011). Thermal inertia is largely influenced by the type of materials, insulation, and layers used in the exterior walls, and thermal resistance depends on the insulation value and reflectivity of the outer layer material, such as the coating. In the included studies, the exterior wall thermal property (PCS10) was the most studied passive strategy, measured with different units, including the U-value, which represents the heat loss coefficient ($W/m^2.k$); the R-value, which represents heat resistance ($m^2.k/W$); thermal conductivity (W/m.k); and specific heat (J/kg.K). Different external finishes and colors (PCS21) were also studied by various researchers, such as Cheung et al. (2005), who found a 30% reduction in solar absorptance of the external walls when using an alternative exterior finish, which can achieve a 12.6% reduction in the cooling load of a high-rise apartment building.

3.2.2. *Exterior roof thermal property and cool roof*

The same measures for the exterior walls can be used for the exterior roof (PCS9), which is the second most studied PCS. In countries with a high intensity of incident solar radiation, roof construction is even more crucial (Mirrahimi et al., 2016). Different roof insulation materials have been studied, including reflective materials (e.g., aluminum foil) and high thermal resistance materials (e.g., polyurethane). The effectiveness of PCS9 is demonstrated in multiple publications and is, overall, more effective than PCS10. According to Vargas and Hamui (2021), the energy savings from PCS10 is 4.9%, while PCS9 can lead to a 13.7% energy use reduction in a single-family house in Mexico. Another study shows the best solution for increasing indoor thermal comfort is to use low-tech and low-cost roofing materials (e.g., water-retaining brick) rather than roof overhang shading (Han et al., 2017). A cool roof (PCS20) as an alternative roof option is useful in hot and dry climates and has been studied in multiple countries (Sghiouri et al., 2020; Mahmoud and Ismaeel, 2019).

3.2.3. *Windows and glazing*

The window and glazing thermal property (PCS12) is the third most studied PCS. Glazing materials and thermal properties have been extensively studied to mitigate external solar heat transfer. Some studies have focused on the thermal property of glazing alone (Rui et al., 2019) or the type of glazing (Onyenokporo and Ochedi, 2019), while others have studied the overall thermal property of entire window units (Teng et al., 2021). The thermal performance of glazing and window units has been measured with different units, including the U-value, which represents the heat loss coefficient ($W/m^2.k$) and solar heat gain coefficient (SHGC). When the U-value decreases, the thermal performance of glazing increases to restrict heat transfer. In all publications, PCS12 was not studied as an individual passive strategy; it was always combined with PCS10, PCS15, PCS17, or PCS16. Consequently, its effectiveness can only be evaluated as a compounding effect.

3.2.4. *Horizontal and vertical shading*

The most effective way to reduce solar heat gain through fenestration is to intercept direct radiation from the sun before it reaches and penetrates the glass. Exterior shading devices dissipate their absorbed heat to the surrounding air, while inside blinds create a heat trap within the indoor space. A fully shaded window can achieve a solar heat gain reduction of as much as 80% (Bradshaw, 2010). Various shading devices have been employed, such as a roof overhang (PCS14), horizontal shading (PCS15), vertical shading (PCS16), exterior louvers, awnings, mesh screening, and other architectural projections.

3.3. *Cooling systems (CS)*

3.3.1. *Cross ventilation (PSC23), night ventilation (PSC24), and evaporative cooling (PSC22)*

Ventilation is the most studied PCS that is applicable in all hot climates. Cross ventilation is a type of ventilation that uses air movement across the skin to promote thermal comfort (Bradshaw, 2010). When air passes over the skin, it can provide a physiological cooling effect by causing moisture to evaporate from the skin's surface. Cross ventilation is particularly appropriate in hot and humid climates. For example, Oropeza-Perez and Østergaard (2014) demonstrated an energy-saving potential of around 54.4% in a Mexican residential sector through utilizing natural ventilation. In hot and dry climates, cross ventilation can be applied where it is appropriate. Alaidroos and Krarti (2016) show cross ventilation (PCS23) alone reduced cooling energy use by 22%, and when combined with evaporative cooling (PSC22), the energy savings can be up to 64%. Nighttime ventilation, which only occurs during the night, is particularly suitable for hot and dry climates since there is a large temperature fluctuation between the daytime and nighttime. Therefore, bringing cool night air indoors is the best possible way to bring down indoor temperatures. Michael et al. (2017) conducted field measurements of the effects of nighttime ventilation, with results showing a positive contribution to the cooling of indoor spaces during the summertime.

3.3.2. *Wind catcher*

A wind catcher (PCS26), also called a wind tower, is a prevalent PCS used in traditional Arab architecture (Friess and Rakhshan, 2017). It takes advantage of the pressure difference by positioning the wind inlet at a high elevation and the outlet at a low elevation. When there is no wind outside, the wind catcher can be combined with a solar chimney (PCS27) to create air temperature differences at different elevations; then, the inlet can act as an outlet for the stack ventilation (Friess and Rakhshan, 2017). A wind catcher is typically effective in climates with high outdoor temperatures. In hot and dry climates, PCS26 can be integrated with PCS22 to provide cool and humid air (Hughes et al., 2012). In addition, a wind catcher can also be used in conjunction with a courtyard to further improve cross ventilation (Al-Sallal et al., 2013). In the reviewed publications, the effectiveness of PCS26 was studied together with other passive strategies rather than for its individual effect.

3.3.3. Solar chimney

A solar chimney (PSC27) is an organized natural stack ventilation method that uses the convention of air heated by passive solar. It comprises a vertical shaft and a solar collector (e.g., a Trombe wall or solar wall). This strategy, which uses solar radiation to enhance natural ventilation, can be found in traditional and vernacular buildings in the Middle East and Europe, with documentation as early as the 16th century in Italy (Di Cristofalo et al., 1989). PSC27 has been included in five publications.

4. Meta-analysis findings

4.1. Passive cooling strategies applied in residential buildings and related measurements

Four measurements were used to evaluate the effectiveness of PCSs: energy savings (%), cooling load reduction (%), indoor temperature decrease (°c), and indoor thermal comfort hour extension (% of hours). However, not all PCSs had associated quantified measurement units. Yang et al. (2020) conducted field measurements on two vernacular houses to study earth sheltering. The air temperature, relative humidity, globe temperature, air velocity, and wall surface temperature were measured during the summer months at 30-min intervals. The results showed earth sheltering was the most effective strategy to satisfy human thermal comfort, followed by night ventilation. However, the data collected only demonstrates a comparison between outdoor and indoor temperatures, rather than an indoor temperature decrease between buildings with and without passive strategies. The researchers found that the indoor air temperature in summer was around 31 °C, while outdoor temperatures exhibited a diurnal variation of 15.7 °C, from 28.6 °C to 44.3 °C (Yang et al., 2020). The quantified measurements were difficult to include in the meta-analysis; therefore, this study was excluded from the analysis but used as a reference to draw conclusions.

In addition, extrapolating an individual PCS was difficult since many studies that used a simulation method investigated several PCSs together. For example, Liu et al. (2020) simulated five PCSs concurrently (PCS10, PCS12, PCS14, PCS16, and PCS17) using an EnergyPlus model, with results indicating the annual cooling load and peak cooling load can be reduced by 56.7% and 64.5%, respectively. Al-Qahtani and Elgizawi (2020) studied a single-family detached house in Saudi Arabia using a different software called Design Builders, in which PCS10, PCS12, PCS15, and PCS18 were simulated together. They found the indoor radiant temperature could be decreased by 16%, from 30.8 °C to 26.1 °C, after applying the PCSs, and the cooling load could be reduced by 41.12%. Therefore, understanding the PCSs' individual and combined benefits is valuable.

Fig. 2 illustrates the applied individual PCSs and associated measurements. The X-axis represents an indoor temperature decrease (°C), and the Y-axis represents a cooling load reduction (%); they are two primary measurements of the effectiveness of passive strategies. The farther right along the X-axis and the higher along the Y-axis, the more effective the PCSs are. The size of the circles and number in the circle in Fig. 2 represents the frequency of those PCSs being studied; for example, the "6" in the PCS15 circle means six publications (studies) include horizontal shading as a PCS. The most studied PCSs are exterior wall (PCS10), glazing/window (PCS12), roof (PCS9), window-to-wall ratio (PCS17), cross ventilation (PCS23), horizontal shading (PCS15), vertical shading (PCS16), orientation (PCS1), and solar chimney (PCS25).

Two important findings can be drawn from Fig. 2. First, the most frequently studied and commonly used PSCs are not necessarily the most effective. For example, PCS10 appeared in 19 publications across five continents, reflecting people's consensus on the importance of the external wall's thermal performance. However, PSC10 has a relatively low indoor temperature decrease, averaging at 1.75 °C, compared to that of PCS12 and PCS15. PCS10's cooling reduction effectiveness is also lower than most other PCSs, averaging at 2.30%.

Second, all PCSs related to windows and their solar control are highly effective in reducing temperature and cooling demand. The most effective PCS in cooling reduction is the WWR (PCS17, 55%), and the most effective PCS for indoor temperature decrease is

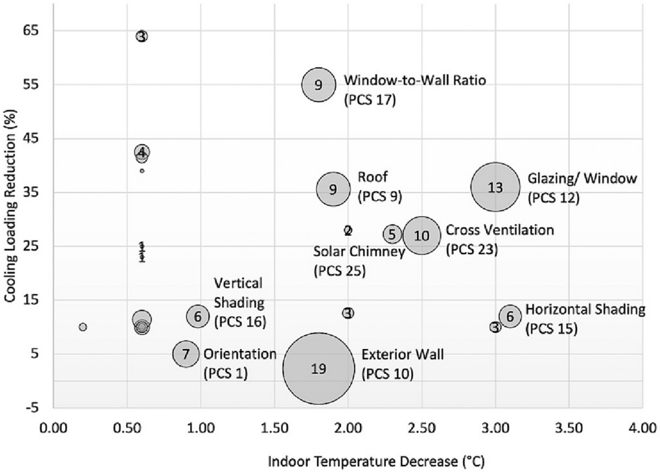

Fig. 2. Applied passive cooling strategies and their measurements.

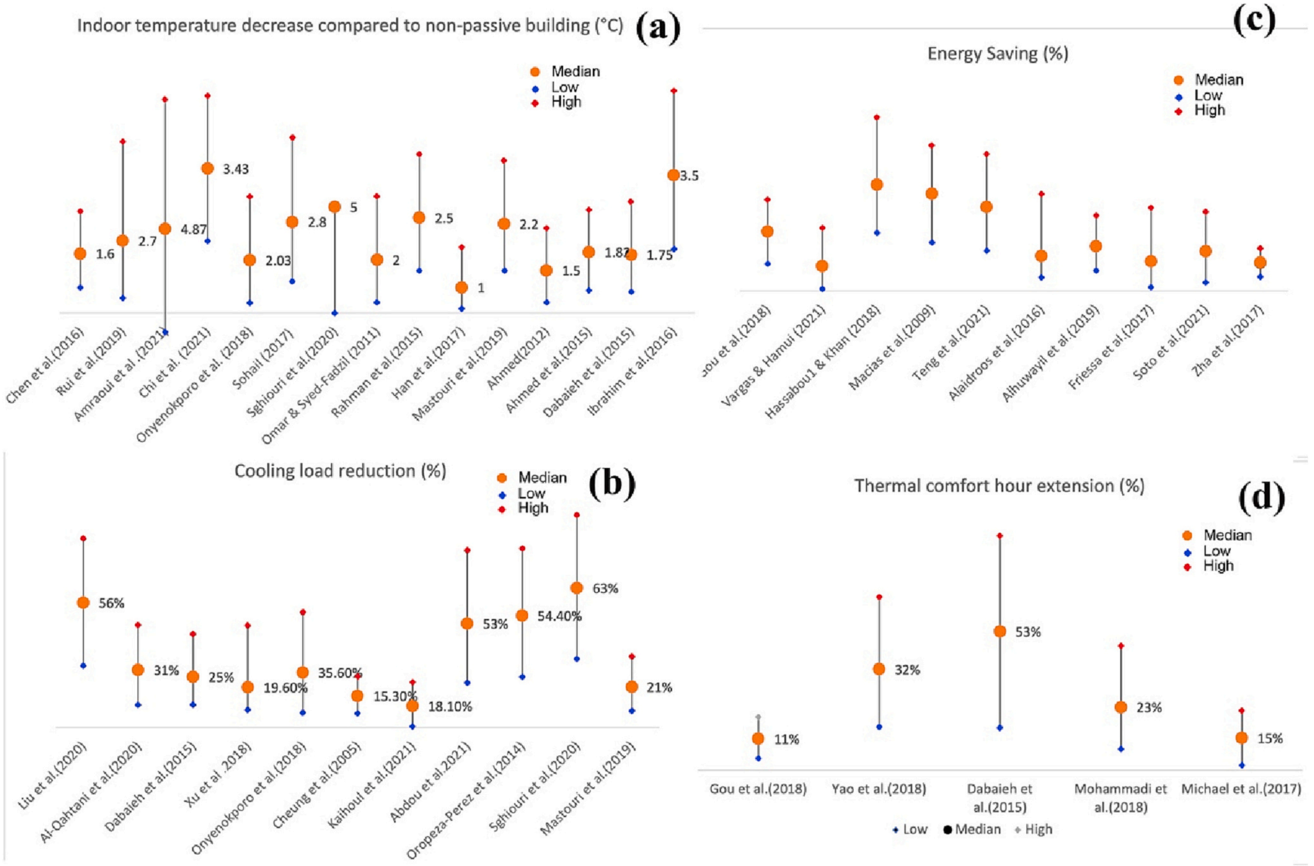

Fig. 3. Effective measurements of passive cooling strategies: (a) cooling load reduction, (b) energy savings, (c) indoor temperature decrease compared to non-passive buildings, and (d) thermal comfort hour extension.

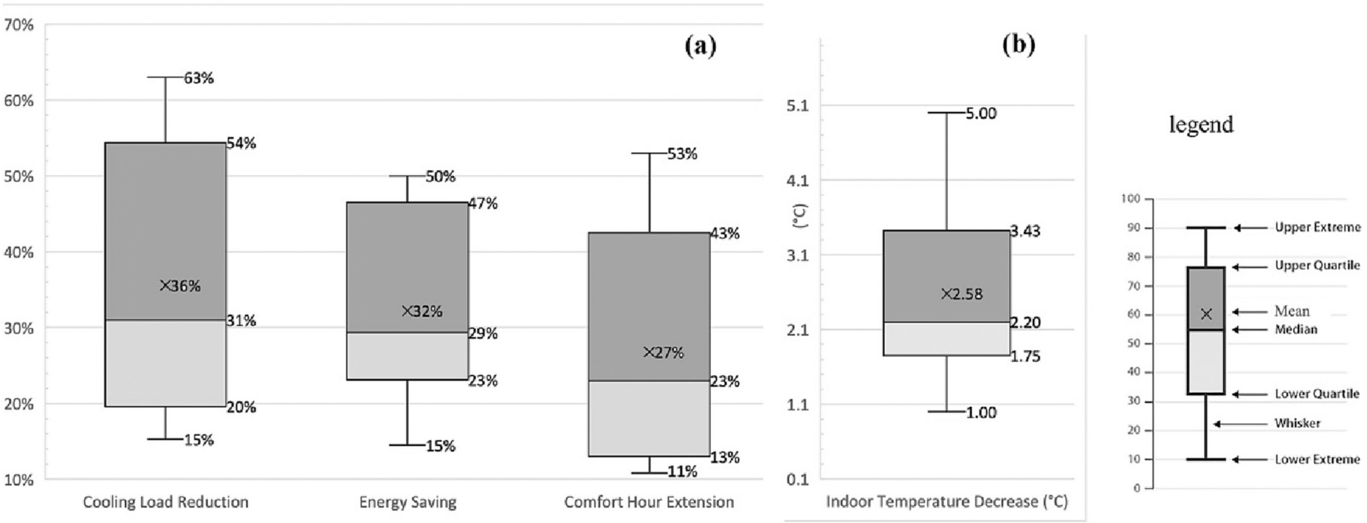

Fig. 4. Effectiveness of combined passive strategies (a) cooling load reduction, energy saving, thermal comfort hour extension. (b) indoor temperature decrease.

horizontal shading (PCS15, 3.6 °C). PCS12 is also effective in a cooling load reduction (36%) and temperature decrease (3 °C). These findings support controlling the WWR and adding shading in hot climates and reinforce previous findings from commercial office buildings. For instance, Troup et al. (2019) analyzed the 2012 CBECS (Commercial Buildings Energy Consumption Survey) and found the WWR is a significant predictor of energy use for cooling and, to a lesser extent, lighting and ventilation. However, in hot and dry climates, the optimal WWR (PCS17) was found to be less than 20% (Kaihoul et al., 2021), while in hot and humid climates, the ratio was recommended to be around 20%–24% (Mirrahimi et al., 2016; Yao et al., 2018). Despite these findings, the optimal WWR is rarely used in modern buildings.

4.2. Benefits of applying passive strategies in a residential context

Fig. 3 demonstrates four measurements of the effectiveness of PCSs. Different studies employed varying measurements; therefore, the measurements in publications did not always overlap. This review aims to provide a better understanding of the effectiveness of passive cooling, thus both individual and combined benefits are included in the analysis. Consequently, a wide range of variations can be observed below. Fig. 3a shows 36% of the studies ($n = 15$) used an indoor temperature decrease to demonstrate the benefits of passive strategies, with the decrease varying between 0.2 °C and 6.1 °C. The highest temperature decrease was achieved in a neo-vernacular three-story apartment building in southern Algeria (Amraoui et al., 2021). The passive strategies applied were PCS1, PCS2, PCS4, PCS10, and PCS15. The project applied traditional techniques to make the exterior bricks (*tufla*) and slabs (*tafza*) while using locally available materials (Amraoui et al., 2021). Another study focused on traditional straw clay housing that used local materials together with passive cool roofs and shading; these low-cost and low-tech buildings can achieve an indoor temperature reduction of 5 °C. These findings are encouraging since they demonstrate that low-cost local materials and techniques can achieve thermal comfort in harsh climates, without the use of expensive, advanced materials. They also demonstrate the wealth of techniques that can be learned from traditional and vernacular building design and construction.

The second measurement is the cooling load reduction (refer to Fig. 3b), with a median value range between 18.1% and 63%. The highest reduction reported was 65%, from a study conducted on Moroccan mid-rise apartment buildings. The results were from a simulation rather than on-site measurements, and the passive strategies tested were PCS1, PCS11, PCS12, and PCS17 (Abdou et al., 2021). The lowest reduction was found in an Algerian study on low-rise single-family detached and attached houses, which represents 20% of the residential sector in southern Algeria (Kaihoul et al., 2021). The research team studied several scenarios with different strategies, including PCS1, PCS11, PCS12, PCS15, PCS16, and PCS17. They found that adding external shading produced the lowest impact, reducing the cooling load by only 0.9%, possibly because the studied buildings already had deep recessed windows with a self-shading effecthus adding additional shading generated a negligible effect. In addition, this study indicated that an increased WWR, from 20% to 40%, can increase the cooling load by 15.96%.

The third measurement is energy savings (refer to Fig. 3c), with the median savings ranging between 14.5% and 49.5%. The highest reduction reported was 70% from studies on mid-rise apartment buildings in Qatar (Khan et al., 2018). The researchers simulated the combined effects of PSC9, PSC10, PSC12, and PSC19. The lowest energy saving (2%) was reported by Vargas and Hamui (2021) who

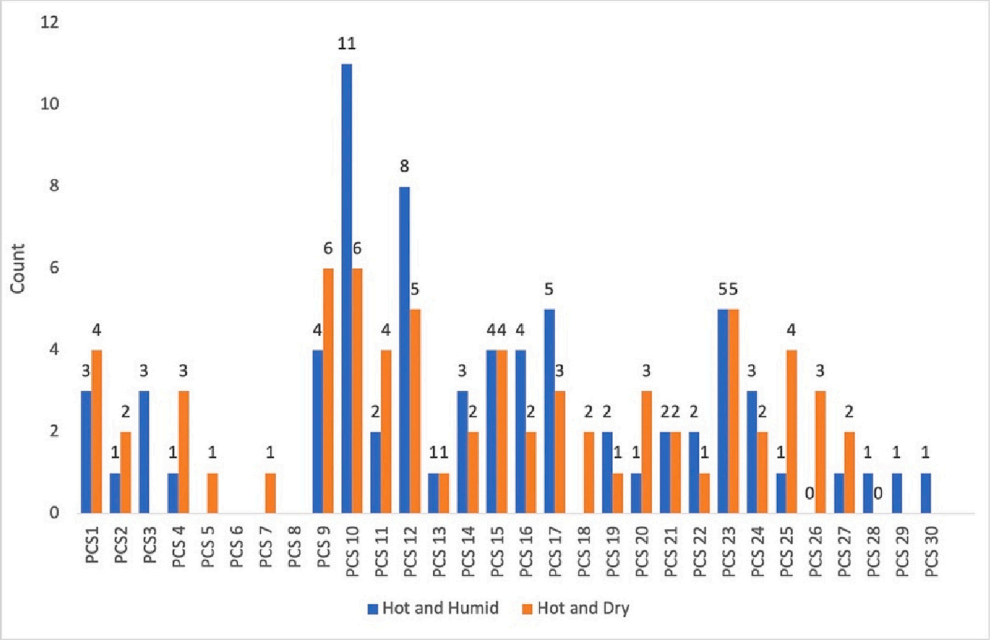

Fig. 5. Application of PCSs per climatic condition.

used a simulation of a single-family attached house in Mexico. To reduce the solar gain, the researchers proposed to add additional glass, with a thickness of 13 mm, to all existing single-pane windows and to change all aluminum frames to wooden frames. Further, the research team found that adding more insulation on the roof could result in a substantial increase in energy savings, at 13.7% (Vargas and Hamui, 2021).

The fourth measurement is the comfort hour extension, which is the least used metric. As listed in Fig. 3d, only five studies used this measure. The median thermal comfort hour extension ranges between 10.8% and 53%. The highest effect (53% extension) was found in mid-rise apartment buildings in Cairo, Egypt, using a combination of PCS4 and PCS20, a vault roof with a rim angle of 70 and high-albedo coatings (cool roof). The comfort hours can be extended from 816 h to 1735 h, which is a significant increase in hot and dry climates (Dabaieh et al., 2015).

Two overall conclusions can be drawn. First, there are consistent, significant benefits of the individual and combined passive strategies in all four measurements in all climate conditions across countries. The empirical evidence, as demonstrated in Fig. 4, concludes that a combination of low-cost passive strategies can lead to an average energy savings of 31%, a cooling load reduction of 29%, a thermal comfort hour extension of 23%, and an indoor temperature decrease of 2.20 °c. Second, studies on passive techniques in vernacular buildings using actual measurements show promising results of indoor temperature reductions in Algeria, China, and Malaysia and of a cooling load reduction in China, Iran, Cyprus, and Algeria (Amraoui et al., 2021; Xu et al., 2018; Kaihoul et al., 2021; Mohammadi et al., 2018; Yao et al., 2018; Michael et al., 2017). These findings demonstrate that localized low-cost design solutions are readily available, and learnings from tradition and vernacular buildings should be prioritized, especially in developing countries.

5. Discussion

Fig. 5 shows a breakdown of the passive strategies' implementation in hot and dry climates and hot and humid climates.

In hot and dry climates, the three most studied and effective passive strategies were increasing the thermal property of the exterior roof (PCS9), exterior wall (PSC10), exterior glazing and window (PCS12), horizonal shading (PCS15), and optimizing cross ventilation (PCS23). Mahmoud and Ismaeel (2019) demonstrated that using roofing materials with a high thermal resistance value can reduce energy use by 73% and the cooling load by 31%. Moreover, Onyenokporo and Ochedi (2019) indicated that increasing the reflectivity of the exterior roof and walls by using low-emissivity paint, combined with external shading, could reduce the cooling load by 37.6% and the indoor temperature by 6.7%. Roof shape (PCS4) is often studied together with PCS9; although it is not among the most applied strategies, it often has a high effectiveness. For example, according to Dabaieh et al. (2015), a vault-shaped roof can decrease the average indoor temperature (in August) by 1.5 °C and the cooling load demand by 25%. The empirical evidence indicates that PSC9, PCS10, PCS12, and PCS23, all together, can be used as indicators to forecast the cooling load, energy use, and thermal comfort benefits of passive strategies in hot and dry climates.

In hot and humid climate regions, the external wall thermal property (PCS10) is the dominating applied strategy, followed by the thermal properties of glazing/window (PCS12), WWR (PSC17), and PSC23. PSC12 and PCS17 are often used together. Solar heat gain through glazing has been proven to be the main factor for an indoor temperature increase. Using reflective glazing, double-pane glass, or Low-E window glazing can help block direct solar heat gain; using smaller windows can also be a solution (Liu et al., 2020). Mohammadi et al. (2018) demonstrated that PSC12 is a critical contributor to an overall indoor thermal comfort hour extension of 34% and energy reduction of 46%. When those strategies are combined, according to Liu et al. (2020), the combined benefit is a cooling load reduction of up to 64.5%. Consequently, PCS10, PCS12, PCS17, and PCS23, when combined, can be used as indicators to forecast the cooling load, energy use, and thermal comfort benefits of passive strategies in hot and humid climates.

The solar chimney (PCS25) has been traditionally studied in hot and dry climates, but according to the review, it can be applied in hot and humid climates, combined with other PCSs as well as low-cost passive cooling systems. Zha et al. (2017) tested a full-scale solar chimney in a three-story building and found the use of solar chimneys has an energy savings of 14.5% in Shanghai, China. Chi et al. (2021) tested coupling a solar chimney with a water-to-air exchanger system in a two-story single-family house in Wuxi, China, and observed an energy savings of about 39%.

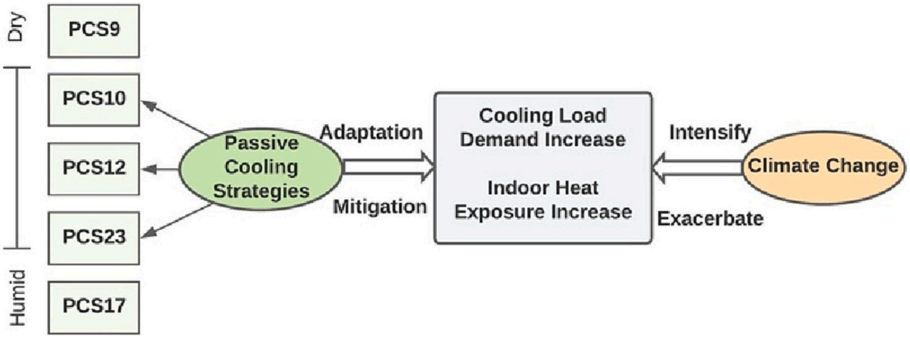

Fig. 6. Conceptual framework for adaptation and mitigation.

6. Conclusion

Climate change will continue to impact the built environment as global warming exacerbates extreme heat events. As a result, many residential buildings are at risk of overheating. Meanwhile, overreliance on mechanical cooling can lead to higher energy consumption. Most research and practice foci have concentrated on active (mechanical) cooling technologies since potential cooling demand reductions through the adoption of passive design have not been fully understood. To the author's knowledge, this is the first systematic review and meta-analysis conducted on empirical evidence of the effectiveness of PCSs. This review includes empirical studies from 2000 to 2021, with 30 passive strategies found and related effectiveness measurements extracted. The meta-analysis provides solid evidence illustrating the benefits of low-cost passive strategies in the categories cooling load reduction, indoor temperature decrease, thermal comfort house extenstion and energy savings. Several passive strategies have been identified as primary factors to be studied and implemented. Based on the review findings, Fig. 6 represents a proposed conceptual framework of major housing PCSs that have mitigation and adaptation effects regarding climate change. Six PCSs were identified as most effective, including PCS10, PCS12, and PCS23, and are applicable in all hot climates. PCS17 is appropriate for hot and humid climates, while PCS9 is suitable for hot and dry climates.

More PCSs can be added for specific locations depending on further studies. This framework can be used to inform future design guidelines, regulations, or policies for new buildings to mitigate future extreme heat events, or for retrofitting existing housing to become more adaptive to the changing climate. The identified climate adaptive PCSs are straightforward and low cost. Their success is also dependent on specific knowledge of the site conditions and certain implementation methods that are unique to individual buildings. This framework merely serves as the first step in identifying and defining the effective PCSs. Conducting further assessments to identify the optimal quantities for specific sites is the next task for individual project teams, local building regulatory agencies, and involved stakeholders.

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

The authors confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Data availability

Data will be made available on request.

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