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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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.

KEYWORDS: passive design, residential building, energy saving, indoor thermal comfort, hot climates

INTRODUCTION

Traditional buildings in hot climates have long used passive design strategies to maintain comfortable indoor temperatures, a practice predating modern air conditioning (AC). These strategies are favored in low-energy buildings to minimize heating and cooling loads. However, there's a global trend towards mechanical AC, with its advent in the early 20th century and mass adoption in the 1950s in the U.S., where now 90% of homes have AC. In contrast, Europe has less than 10% AC penetration. AC adoption is surging in developing nations like China and India. As climate change exacerbates heat extremes, reliance on AC is expected to grow, evidenced by the tripling of global AC sales from 1990 to 2016. (IEA 2018)

Over-reliance on air-conditioning systems presents three significant issues. Firstly, it leads to a surge in energy use, as cooling systems currently draw about 20% of global electricity, contributing to 8% of energy consumption in U.S. homes. This trend may escalate global energy demand and related carbon emissions. Secondly, the heavy reliance on air-conditioning strains power grids, especially during heatwaves in developing nations, risking power outages when demand exceeds supply. Finally, there's an issue of environmental injustice; climate change intensifies weather extremes, impacting disproportionately on marginalized groups. Heatwaves, now the deadliest weather phenomenon, afflict the elderly, young, pregnant women, and those with certain medical conditions or socioeconomic disadvantages the hardest, across both affluent and cooler regions.(Kravchenko et al. 2013; Zuo et al. 2015).

To adapt to more frequent and intensified heatwaves caused by climate change while minimizing energy consumption increases 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 the 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) it is 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 thermal comfort. There are a few reviews 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?

1.0 METHOD AND MATERIALS

1.1. 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, Chang-Richards, and González 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).

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; (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 Figure 1, initially, a total of 339 publications were identified from Web of Science (n=231), ProQuest (n=72), and PubMed (n=36). The disciplines and fields included 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 screening by reading through the abstract of all founded articles. After the abstract screen, 133 publications were selected for full-text eligibility assessment using the abovementioned criteria. After the full-text assessment, 42 articles were included for meta-analysis, synthesis, and conclusion-building.

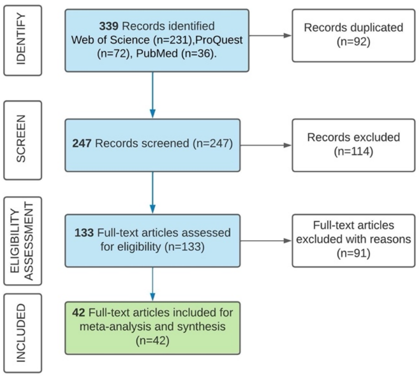

Figure 1: Flowchart of the review process Source: (Author 2023)

1.2. Meta-analysis

Unlike a systematic review, a meta-analysis is a statistical synthesis of the results of previous studies that similarly addressed a related hypothesis (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 sustainability methodologies in construction ￼ and investigate buildings' embodied energy and carbon (Minunno et al. 2021). However, the use of meta-analysis is limited to 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.

2.0 FINDINGS

2.1. Overall description

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. The following sections will provide explanations of primary passive strategies included in this study. The primary passive strategies are those that were studied by more than three publications. The selected PCSs have been grouped into three passive strategy categories: design approach (DA), building envelope (BE), and cooling system (CS).

Table 1: Passive cooling strategies. Source: (Author 2023)

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

2.2. Meta-analysis findings

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-minute 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 conclude.

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 & 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 that the indoor radiant temperature could be decreased by 16%, from 30.8°C to 26.1°C, after applying the PCSs, and that the cooling load could be reduced by 41.12%. Therefore, understanding the PCSs' individual and combined benefits is valuable.

Figure 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 the number in the circle in Figure 2 represent 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).

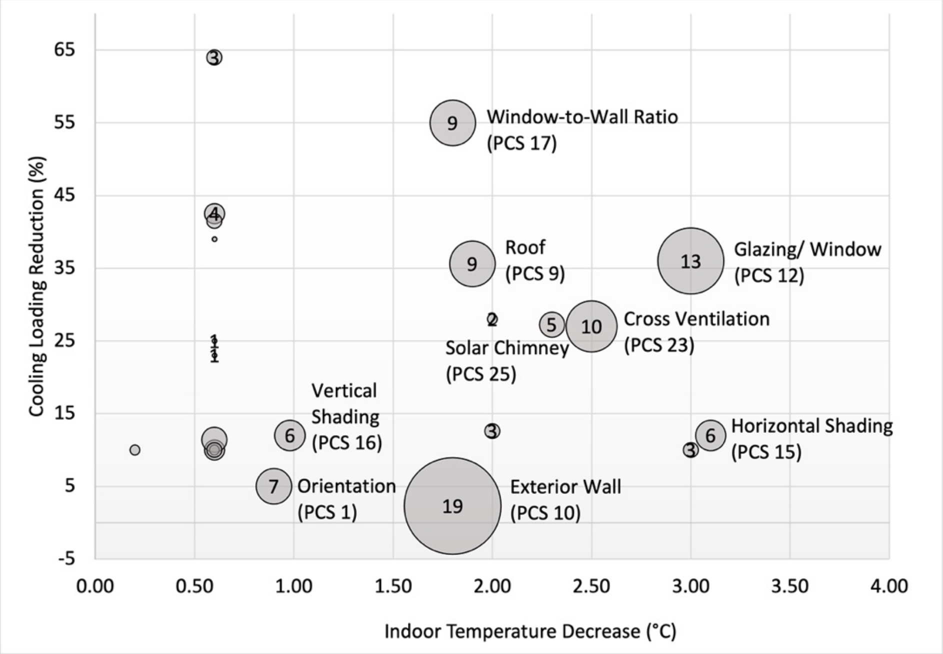

Figure 2: Applied passive cooling strategies and their measurements. Source: (Author 2023)

Two important findings can be drawn from Figure 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 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% Yao et al. 2018). Despite these findings, the optimal WWR is rarely used in modern buildings.

2.3. Benefits of applying passive strategies

Figure 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. Figure 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 Figure 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 represent 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 effects 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%.

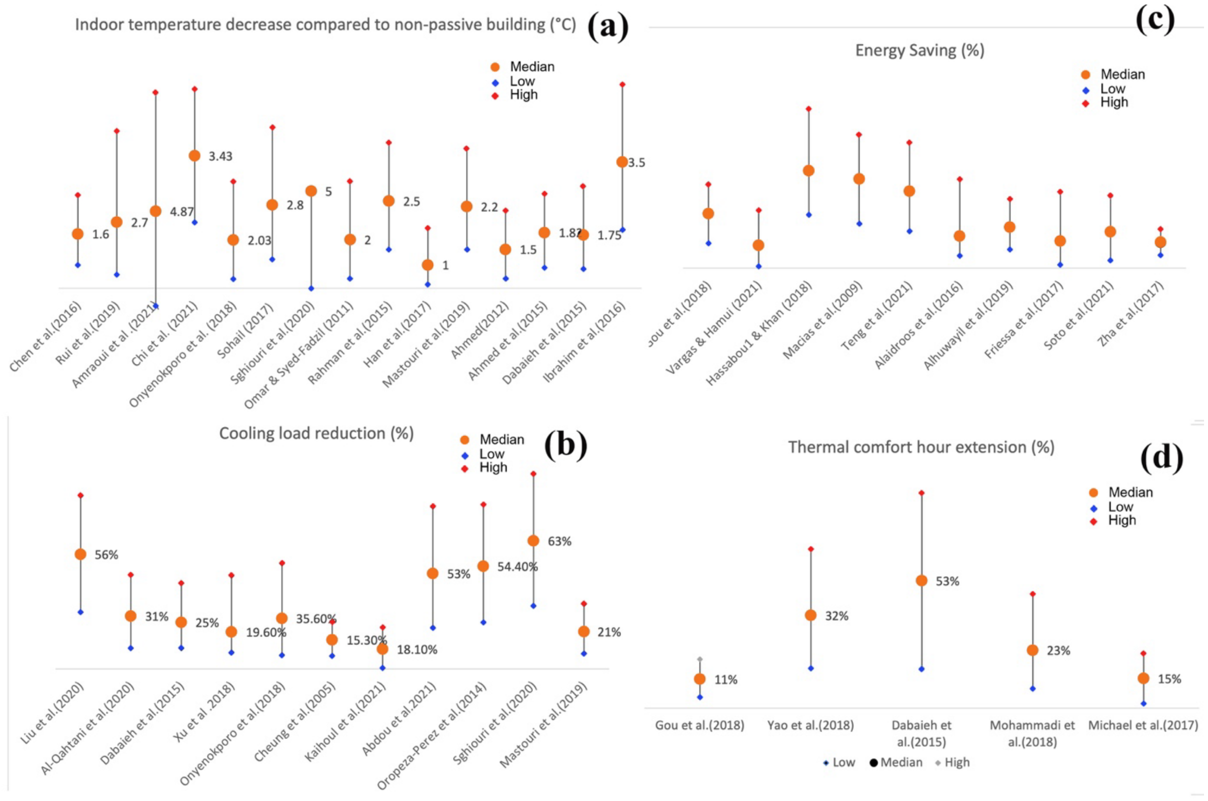

Figure 3: Effective measurements of passive cooling strategies: (a) cooling load reduction, (b) energy savings, (c) indoor temperature decrease compared to non-passive buildings, and (d) thermal comfort hour extension. Source: (Author 2023)

The third measurement is energy savings (refer to Figure 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 & Hamui (2021) who used a simulation of a single-family attached house in Mexico. To reduce the solar gain, the researchers proposed adding additional glass, with a thickness of 13 mm, to all existing single-pane windows and changing 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, the least used metric. As listed in Figure 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 hours to 1,735 hours, 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 Figure 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 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 traditional and vernacular buildings should be prioritized, especially in developing countries.

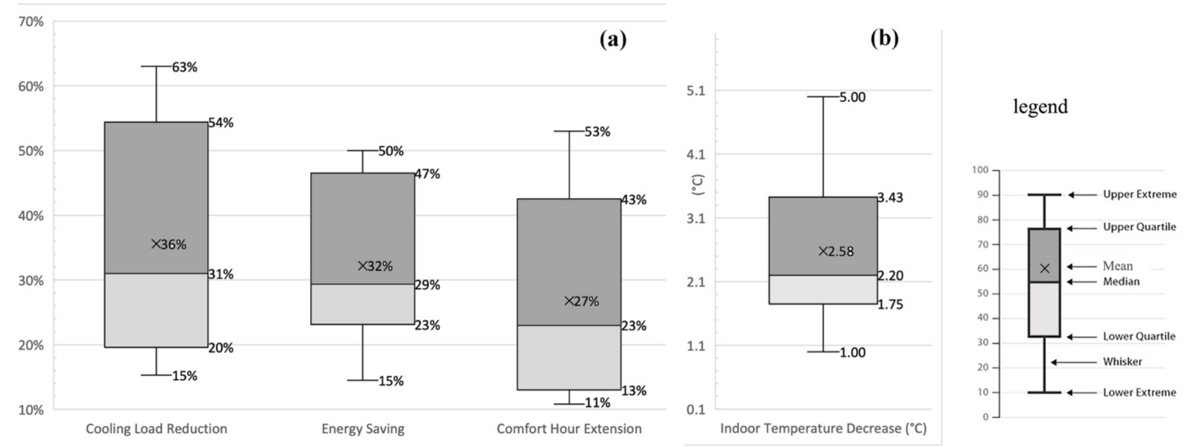

Figure 4: Effectiveness of combined passive strategies (a) cooling load reduction, energy saving, thermal comfort hour extension. (b) indoor temperature decrease. Source: (Author 2023)

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 of cooling load reduction, indoor temperature decrease, thermal comfort house extension, and energy savings. Several passive strategies have been identified as primary factors to be studied and implemented. Based on the review findings, Figure 5 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.

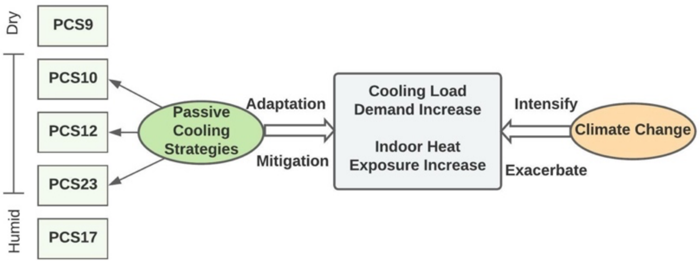

Figure 5: Conceptual framework for adaptation and mitigation. Source: (Author 2023)

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.

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