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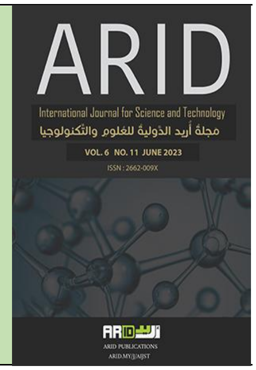

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Passive Cooling Strategies in the Hot-humid Climate: A Review Study

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استراتيجيات التبريد السلبي للمباني في المناخ الحار الرطب: دراسة مرجعية

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ABSTRACT

Recently, passive cooling strategies have gained more attention as an alternate method of cooling and ventilating indoor areas as part of a push toward more sustainable architecture. Passive cooling relies on free and sustainable energy sources such as the sun and wind to provide the necessary cooling, ventilation, and lighting for buildings to provide a comfortable indoor environment, therefore, the electrical energy that required for mechanical cooling can be reduced. The studies showed that these solutions have the potential to save good amount of building's cooling energy annually -about 23.6%-, depending on building type, construction materials, windows' area and other specifications. In spite of that, the specifications need to be implemented and well-designed in an integrated system. This paper aims to review and discuss the possible passive cooling strategies that can be implemented in the hot-humid climate as a step towards decreasing energy consumption. A review of the literature has been done by searching for the appropriate keywords. It was found that many studies have highlighted the significance of using several types of passive cooling strategies for enhancing thermal comfort inside the buildings in the hot-humid climate, while some other strategies are not recommended. Protecting the buildings from direct solar radiation and applying natural ventilation to the buildings are the most effective passive cooling strategies that can be used in the hot-humid climate. The study recommended to review the appropriateness of several types of passive cooling strategies in different types of climates to highlight the most appropriate passive cooling strategies for each type of climate.

Keywords: Passive cooling, Natural ventilation, Green building, Thermal comfort, Building sustainability.

الملخص

اكتسبت استراتيجيات التبريد السلبي للمباني مزيدًا من الاهتمام في العقد الأخير كطريقة بديلة لتبريد وتهوية المناطق الداخلية سعياً للتوجه نحو أبنية أكثر استدامة، حيث يعتمد التبريد السلبي على مصادر الطاقة المجانية والمستدامة مثل الشمس والرياح لتوفير التبريد والتهوية والإضاءة اللازمة للمباني لتوفير بيئة داخلية مريحة، حيث يمكن تقليل الطاقة الكهربائية المطلوبة للتبريد الميكانيكي. وأظهرت الدراسات أن هذه الحلول لديها القدرة على توفير كمية جيدة من طاقة تبريد المبنى سنويًا - حوالي 23.6٪ - اعتمادًا على نوع المبنى ومواد البناء ومساحة النوافذ والمواصفات الأخرى. وعلى الرغم من ذلك، فإن هذه المواصفات تحتاج إلى تنفيذ وتصميم جيد في نظام متكامل. وتهدف هذه الورقة إلى مراجعة ومناقشة استراتيجيات التبريد السلبي التي يمكن تنفيذها في المناخ الحار الرطب كخطوة نحو تقليل استهلاك الطاقة. حيث تم إجراء مراجعة للأدبيات باستخدام الكلمات المفتاحية المناسبة. وقد وُجد أن العديد من الدراسات قد ناقشت أهمية استخدام أنواع عديدة من استراتيجيات التبريد السلبي لتعزيز الراحة الحرارية داخل المباني في المناخ الحار الرطب. وقد تم إجراء هذه الدراسة لتمهيد الطريق لاختيار استراتيجيات التبريد السلبي المناسبة التي يمكن أن توفر الراحة الحرارية وتحقيق أفضل توفير للطاقة في المناخ الحار الرطب.

الكلمات المفتاحية: التبريد السلبي، التهوية الطبيعية، المباني الخضراء، الراحة الحرارية، استدامة المباني.

1. Introduction:

The world's most pressing environmental issues are global warming and ozone depletion, as well as lack of energy supplies [1-4]. The overreliance on fossil fuels have the large portion of global energy demand recently. As a result, energy resources, which are non-renewable, is expected to be drained in the near future. Therefore, non-renewable energy resources are expected to be depleted. Energy consumption is expected to rise in the coming years as a result of population growth and technological advancement [5]. Changing in the climate and growing in the economic will increase the demand on cooling energy in the tropical region (which is described as a hot region all over the year), necessitating immediate adaptation in the construction sector to mitigate the issues posed by future increment in cooling energy demand [6]. High energy consumption will also harm the environment and worsen the effects of climate change. Tropical and semitropical areas use significantly more energy than other regions, primarily to meet cooling needs. However, cooling loads can be reduced by using energy-efficient designs and methods [7-10]. Passive cooling has been introduced as an environmentally friendly energy saver, and its effectiveness and sustainability have been investigated [11].

In contrast to the use of active mechanical equipment for cooling and ventilation, passive cooling is typically considered as a combination of natural techniques and approaches for lowering indoor temperatures. Passive cooling solutions have demonstrated excellent efficiency in buildings and can contribute significantly to reduce building cooling loads. Numerous studies have tested and evaluated effective passive techniques. In addition, Passive cooling has demonstrated good thermal comfort and indoor air quality while using low amount of energy. Buildings that use passive cooling methods have shown a reduction in their cooling load by up to 70% [12]. The term "passive cooling systems" has been defined by Givoni [13] as "various simple cooling techniques that enable the indoor temperatures of buildings to be lowered through the use of natural energy sources". Moreover, Givoni clarified that using a fan or a pump is not excluded when their application could improve the performance.

The study of Santamouris and Asimakopoulos [12] showed that there are three main categories of passive cooling techniques. The first technique depends on protecting buildings' envelops from solar radiation and heat gain by using landscaping and vegetation, using outdoor and semi-outdoor spaces, building form, layout and external finishing, colour of buildings' envelop, shading of building surfaces, thermal insulation, windows' size and window to wall ratio, orientation, etc.

The second method that mentioned by Santamouris and Asimakopoulos [12] depends on controlling thermal storage capacity of building structure. This strategy can reduce cooling load peaks and modulates the internal temperature with the heat discharge later. The greater the temperature swings in the outside, the greater the impact of this storage capacity. In order to avoid overheating in the discharge phase, the cycle of heat storage and discharge should be combined with means of heat dissipation, such as night ventilation.

While the third method depends on heat dissipation, which treats with the potential for the disposal of building's excess heat to a lower temperature environmental sink and the establishment of a suitable thermal coupling between the building and the sink as well as an effective temperature variances for the transfer of heat. The potential of heat dissipation techniques are strongly depending on climate conditions. The techniques are known as hybrid cooling if heat transfer is supported by mechanical devices.

Several scholars have outlined various passive cooling strategies in different climate conditions for buildings in order to improve building energy performance. Some of these strategies are old, while others have only been around for a few years. Numerous analyses, simulations, case studies, experimental and modeling investigations have been conducted [14-20].

Other researchers have focused on the possibility of achieving passive cooling strategies in hot-humid climate as options for reducing the energy and environmental impacts of air-conditioning, which is critical in the future [21-24]. The study of Gamero-Salinas et al. [25] underlined the need of passive cooling and overheating prevention design solutions in tropical regions. Al-Tamimi & Fadzil simulation study [26] discussed using shading devices as a solution for minimising solar heat gain through building design in the hot-humid climate of Malaysia. Sulaiman's experimental study [27] examined the use of green façade in Malaysia's hot-humid climate as well. Applying natural ventilation strategies for windows opening have been discussed by other researchers [28, 29]. Using solar chimney in reducing indoor air temperature and increasing air velocity were also discussed by Agung Murti Nugroho [30] which is proved to be effective strategies to increase indoor thermal comfort and minimising energy consumption in the hot-humid climate of Malaysia.

The study of Mirrahimi et al. [31] reviewed the findings of previous studies to determine the proper building envelope parameters for high-rise residential buildings in tropical climate. The study showed that passive cooling strategies are very effective for cooling the buildings in the hot-humid climate. In addition, the study revealed that there is strong effect of different building components, including shading devices, external wall, external roof and external glazing and insulation, and reducing the energy that used for cooling. Moreover, in order to eliminate the dependency on mechanical systems in the buildings, the study recommended to consider the total thermal performance of all components of building's envelope, such as an optimal window-to-wall ratio, appropriate material for glazed windows, and the appropriate shading equipment. Briefly, the study focused on the effect of building envelop on indoor thermal comfort.

Another study conducted by Bhikhoo, Hashemi, and Cruickshank [32] in the hot-humid climate (Thailand) and used IES-VE (Integrated Environmental Solutions-Virtual Environment) simulation software proved that indoor overheating can be reduced in the tropics if proper building design principles for these climate zones are used. Moreover, the same study revealed that roof material and the presence of balconies were found to have the greatest influence on indoor thermal comfort. On the other hand, the study of Tong et al. [33] that was conducted in the hot-humid climate (Singapore) and used parametric method proved that reducing façade's window-to-wall ratio have a good impact on deceasing indoor air temperature.

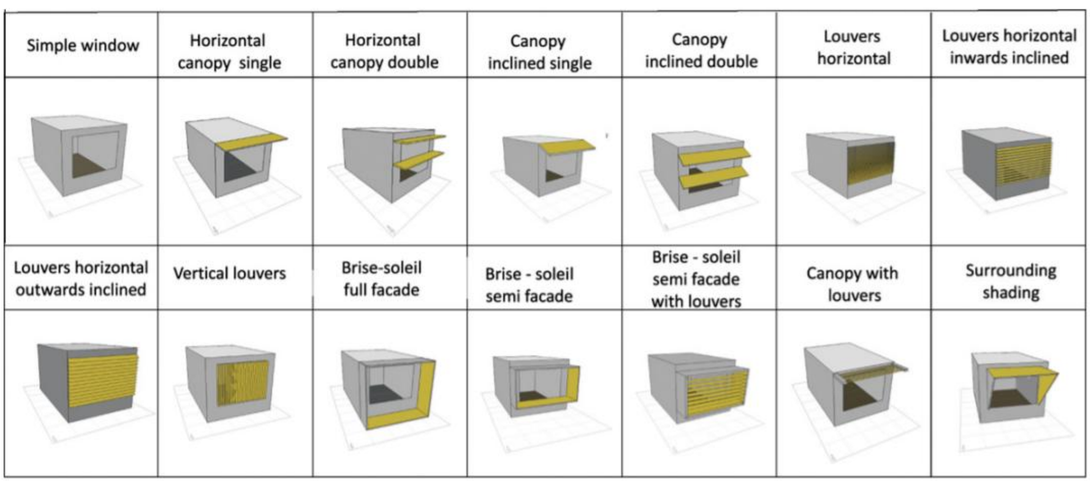
2. Methodology

This study has been conducted to give a sufficient review of the possible passive cooling strategies that can be used in the hot-humid climate to reduce the load on mechanical means and reduce energy consumption, based on the categories of passive cooling strategies that mentioned in the study of Santamouris and Asimakopoulos [12]. The three categories and their passive cooling strategies can be explained as follows:

2.1 The first strategy that depends on protecting buildings' envelops from solar radiation. The following strategies can be used for this purpose.

a- Shading devices: Normal and louvered shading devices can be placed on buildings' façades and can be designed in variety of shapes and sizes in order to block direct solar radiation while allowing wind to pass through the windows and cool the interior environment. They can be positioned horizontally and vertically, or can be louvered which can be adjusted and rotated to provide the optimum results [34]. Figure (1) shows different designs of shading devices.

Another study [35] proved that -in the tropical climate- protecting the windows from solar radiation by adding shading devices and closing the curtains resulted in the lowest indoor operative temperature compared to other investigated strategies that were examined in the study.



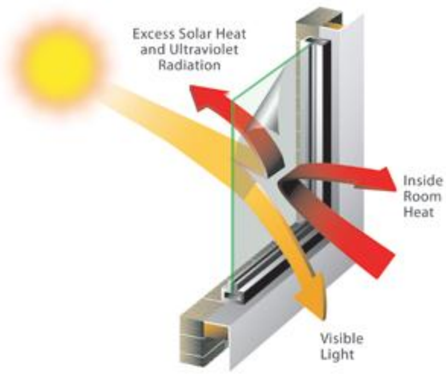
Figure(1): Different designs of shading devices.
Source: [36]

b. Double glazing: Windows are the main element of exchanging large amounts of heat between building's structure and outside environment. However, when compared to single-glazed windows, double glazing has been shown to be effective at reducing heat transfer. The distance between the two glass panels determines how well windows are insulated. The cavity between the two glass panels can be vacuumed or filled with gas [34, 37]. Figure (2) shows the double glazed windows.

Figure(2): Double glazed windows
Source: [37]

c. Solar reflective film for windows: Solar control film comes in a variety of grades and types, each with a particular amount of performance. Each film is created with the goal of reducing heat transfer by reflecting a portion of the sun's solar radiation. The film can assist to reduce the inside temperature from rising to uncomfortable levels by efficiently rejecting a percentage of the heat that comes from solar radiation [38].

The numerical study of Xamán et al. [38] that was conducted in the hot-humid summer in Mexico revealed that employing solar control film in a double glazed window in hot- humid climates might lower energy consumption within the building by approximately 52% when compared to a regular double glazed window. Moreover, the simulation study of Al-Tamimi and Qahtan [39] that was conducted in the hot-humid climate (Malaysia) recommended the use of reflective single or double glass can decrease indoor air temperature throughout the day. Figure (3) shows how solar reflective film works.



Figure(3): Solar reflective film for windows.
Source: [40]

d. Using light colours in coatings with high reflection: Exterior walls are exposed to solar radiation, and can transfer a significant amount of heat to a building; as a result, the temperature of interior environment and the level of comfort can be affected [41]. Solar reflective coating can be used to minimise heat transmission and lower the temperature of the interior space. However, the colour of coating depends on the climate and the type of material utilised. Considering these parameters can lead to energy being saved, especially during the peak time. When bright colour of the exterior walls are compared to dark colour, there is a significant difference, demonstrating the importance of solar reflectance of building envelop [29].

Taleb [34] used three different types of coatings to determine the impact of each type on energy consumption. The first type was standard coating, whereas the second and third had a higher rate of reflection. These various types of coatings were applied to three different walls in order to determine the surface and indoor temperatures, as well as their impact on energy efficiency. The reflection levels for each coating were 32%, 42% and 61% respectively. The study concluded that coating the building with highly reflective coatings can limit heat transfer from the exterior walls to the interior space. This had an effect on the building temperature and as a result, increased thermal comfort inside the building. In addition, using a paint with a 61% reflection of the spectrum had a beneficial effect on energy saving. On the other hand, a recent experimental study conducted by Wang et al. [42] in the hot climate of China proved that using retro-reflective (RR) coatings can give better cooling potential than the Highly-reflective (HR) coatings in the high-density areas.

e. Green roofs and walls: Buildings' roofs are the most elements that exposed to solar radiation, thus, protecting roofs from solar radiation is necessary to avoid indoor overheating. Cooling is a crucial demand of buildings, particularly in the hot-humid climate [43]. Therefore, green roofs have been introduced by the researchers as a sustainable passive cooling strategy. According to Jaffal et al. [44] green roof can be defined as a "building roof covered by grasses or plants which lie over a waterproof membrane". A review of the literature indicated that green roofs are the most effective way to insulate roofs. As mentioned previously, the roof is one of the main surfaces of the building that exposed to high solar heat, so employing a high amount of insulation can help to limit heat transmission to the inside. Besides, there are other significant sustainable advantages that green roofs can provide such as providing oxygen to the environment, reducing the urban heat island effect, and lowering air temperature [34, 45].

Green walls, on the other hand, have recently become a topic of discussion. Green walls can be classified into different types based on the local environment, plant species, and the type of the building itself [46]. Sulaiman [27] discussed in details several types of plants and the shading that each type can provide to achieve the best air temperature reduction inside buildings in the hot-humid climate of Malaysia.

f. Orientation: Studies concluded that in the tropical hot-humid climate, façades that facing the north and south is preferable over façades facing east and west. Therefore, it is recommended to provide the north and south sides of the buildings with large openings for cross ventilation, while protecting the east and west external walls with appropriate building construction materials to avoid high solar heat gains [47]. Additionally, when combining Polymer Dispersed Liquid Crystal (PDLC) glazing with southern and the northern windows' orientation for the tropical climate of Singapore, energy consumption was the less as solar radiation was less in these two orientations [48]. However, the study of Dutta et al. [49] that was conducted in India found that in a tropical climate of the northern hemisphere, heat gain through south-facing windows is the greatest, followed by east, west, and north-facing windows. The differences in the results of these studies could be attributable to different locations where the studies have been conducted (Singapore and India).

g. Insulation and using proper construction materials: To limit heat loss or gain throughout buildings' envelopes, passive design should include insulation. Insulation functions as a thermal barrier, preventing heat gain from the outside. As a result, insulation is used in the walls, ceilings, and floors, and it comes in a variety of forms [50].

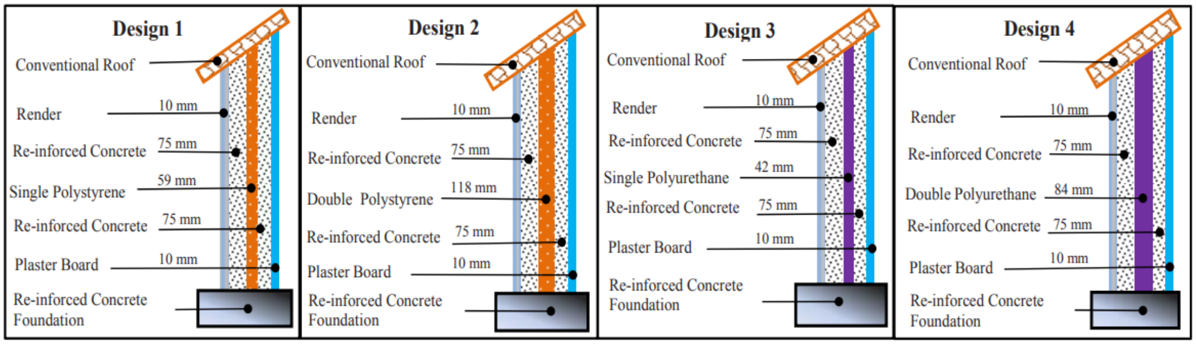
According to Mirrahimi et al. [31], applying appropriate thermal insulation in building envelope is the one of most effective method to reduce heat transmission through the envelop and reduce energy consumption of internal cooling and heating.

Understanding the environmental influence on buildings and the thermal comfort of their occupants is necessary for designing passive energy solutions. In hot-humid climates, building materials absorb heat for the majority of the day [51]. Construction materials play significant role in achieving thermal comfort [52, 53]. The indoor thermal environment is greatly influenced by the local climate. As building envelope separates the inside space from the outer environment and limits the amount of heat flow through itself, selecting the appropriate building envelope material that appropriate for the outdoor climate is highly effective parameter that impacts the indoor environment [54-56].

Furthermore, building's characteristics influence the effect of the outer environment and play an important part in determining the indoor thermal conditions. The influence of local climate on indoor thermal comfort, according to Raja et al. [57], manifests in heat transmission from the outer environment through building materials, where building envelope adjusts heat transmission based on its thermal mass and insulation.

Aldawi et al. [55] found that the new design wall systems -which used different construction materials- required less cooling and heating energy for 9 cities in Australia -including the cities that located in the hot- humid climate- when compared to the old traditional building method of brick veneer and weatherboard houses. Figure (4) shows the traditional building methods in Australia. Figure (5) shows the new design wall systems that suggested by the mentioned study.

Figure(4): Brick veneer and weather board walls in Australia (Traditional method). Source: [55]



Figure(5): New house wall designs with different insulation materials and thickness. Source: [55]

In comparison to polystyrene insulation material, the same study [55] found that polyurethane insulation material saves much more energy (almost 40%). However, doubling the thickness of both materials reduces energy use by 5 to 10%. Based on these results, economic analysis and life cycle evaluation should be conducted to determine which of these two materials is better to be used as thermal insulation.

The experimental study of Kolokotroni et al. [54] that was conducted in the tropical climate [Jamaica, Northeast Brazil and Ghana] mentioned that the thermal characteristics of materials used for external walls and roofing can have a substantial impact on the surface temperature as well as the amount of heat transferred across building surface.

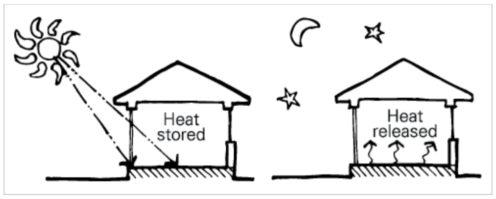
The effect of building materials in enhancing thermal comfort in hot-humid conditions has been extensively discussed in a review study by Latha et al. [58]. The study focused on the use of certain materials in building's envelope to improve thermal comfort, such as vacuum insulation panels (VIPs), phase change materials (PCMs), autoclaved cellular concrete (ACC), and polymer skin. Light-coloured external surfaces, reflecting paints, window treatments, and roof gardens are also mentioned in the same study as popular methods for reducing buildings' heat load.

From the previous literatures, it can be conclude that protecting the buildings from solar radiation and using appropriate insulation and building materials in the countries that have high solar radiation is effective to reduce indoor temperature and cooling loads.

2.2 The second strategy is contingent upon controlling thermal storage capacity of building structure which can be achieved through using high thermal storage materials (or thermal mass). As mentioned previously, this strategy depends on reducing cooling load peaks while modulating the internal temperature with the heat discharge later by combining it with another cooling method during the discharge phase to avoid overheating inside the buildings. Brick, concrete and tiles as high thermal mass materials, act as a storage for heat as they heat up and cool down relatively slowly [12].

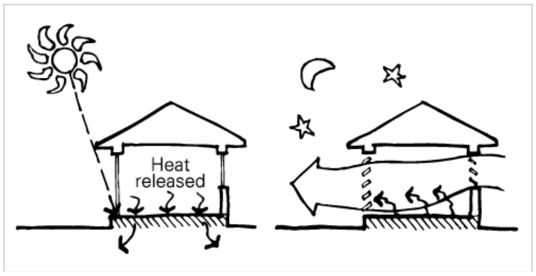
Thermal mass can be defined as "the ability of a material to absorb, store and release heat energy". Thermal mass absorbs thermal energy when the environment is hotter than the mass and gives it back when the environment is cooler, but it never reaches thermal equilibrium [59].

In winter, thermal mass can absorb heat from direct sunlight or radiant heaters during the day. The warmth is then re-radiated into the residence throughout the night. Figure (6) shows thermal mass performance in winter.



Figure(6): Thermal mass performance in winter.
Source: [60]

The same performance in summer, however, allowing cool night breezes and/or convection currents to pass over the thermal mass through natural ventilation, removing out all the stored heat. During the day, using shading and insulation to shield the thermal mass from the hot solar radiation is preferable. Figure (7) shows thermal mass performance in summer.



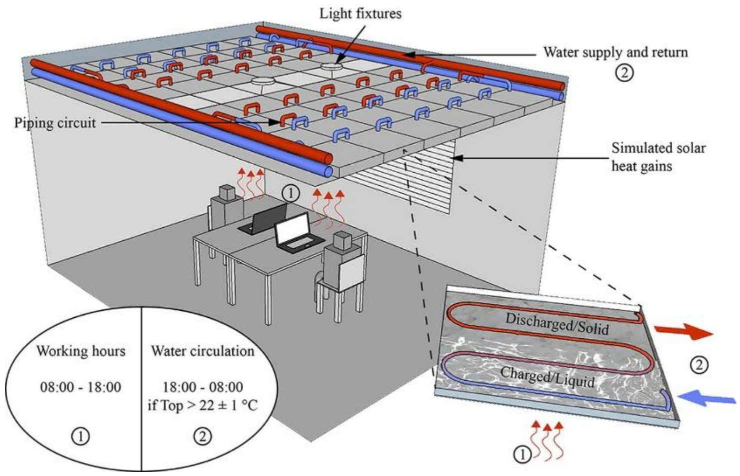
Figure(7): Thermal mass performance in summer.
Source: [60]

Sharaf [61] found that in a semi-arid hot climate, high thermal mass construction materials such as clay-bricks help to keep the indoor environment within the human thermal comfort zone. As a result, the amount of energy required to maintain the room's thermal comfort is considerably lowered.

The usage of thermal mass was investigated in both temperate and tropical regions by Juarez [50]. The study discussed that thermal mass was effective in temperate climates. In a tropical climate, however, light weight design with minimal thermal mass is preferred. Thermal mass is beneficial if the building's free running temperature response is considered in the comfort limits; otherwise, it increases energy demand. Therefore, it can be conclude that this type of passive cooling strategy is not effective in tropical climate.

2.3 The third method is based on heat dissipation by transferring excess heat from a building to a lower-temperature environmental sink, and it is significantly influenced by environmental factors. If heat transfer is aided by mechanical devices, the process is known as hybrid cooling. The most applicable techniques for heat dissipation include ventilation cooling and radiative cooling [12].

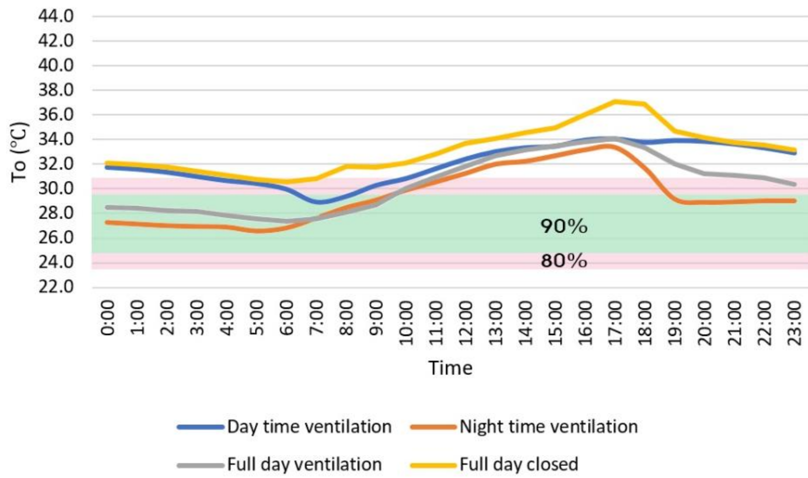
a. Radiant cooling: Radiant cooling is a method of cooling a floor or ceiling by absorbing the heat emitted from the rest of the space. Radiant floor cooling refers to the cooling of the floor; radiant ceiling cooling refers to the cooling of the ceiling in homes with radiant panels and pipes. The majority of radiant cooling residential applications use aluminium panels hanging from the ceiling to circulate chilled water. The panels must be kept at a temperature extremely close to the dew point within the house to be functional, and the house must be kept dehumidified. Simply opening a door in a humid climate may bring enough humidity into the residence to cause condensation [62]. Figure (8) shows radiant ceiling cooling.



Figure(8): Radiant ceiling cooling.
Source: [63]

b. Natural ventilation: Several studies mentioned that one of the most common and effective strategies for thermal comfort in tropical climate is the use of natural ventilation [22, 25, 29, 30, 39, 47, 51, 53, 64-69]. Doors, blinds and curtains, fans, central cooling, and air blowers are the most common controls available for the occupants in natural-ventilated structures; nonetheless, windows are the most significant controls of the indoor environment [57]. If the occupants are dissatisfied with the thermal environment, they will seek to reclaim their comfort. Usually, they use building controls to increase their comfort in different ways. In every building, the first action that occupants normally do to correct their comfort is opening the windows, particularly when the outdoor temperature is acceptable [70]. It is not only valuable for lowering energy usage during the hot season, but also provides an efficient interaction between the indoor and outdoor environments [71].

In addition, Jamaludin et al. [53] examined natural ventilation technique in low-rise multi-residential building in Malaysia and found that night-time ventilation was the best method, followed by daytime ventilation, full-day ventilation, and no ventilation. This result was supported by another study which examined different types of ventilation to find the best ventilation that can achieve thermal comfort in the hot-humid climate of Malaysia. The results showed that applying night ventilation by opening the windows and the internal doors during the night -to permit the cool nocturnal air to inter the building- and closing them during the daytime -to prevent the hot diurnal from interring the building- can eliminate the diurnal indoor air temperature and keep the indoor space within the comfortable temperature [68]. Figure (9) shows the effect of nigh ventilation on indoor operative temperature.



Figure(9): The effect of nigh ventilation on indoor operative temperature.
Source: [68]

Another study conducted by Daghih et al. [69] concluded that the office that have a combination of windows-door opening performed better in terms of air exchange rate, age of the air and air efficiency than the opening the windows and closing the doors of the office.

From the previous studies, it can be concluded that radiant cooling is possibly effective in arid settings, while it is problematic in the hot-humid climes. Additionally, applying natural ventilation is very effective to improve indoor thermal comfort in the hot-humid climate.

c. Combination of different strategies: Some studies combined various passive cooling strategies to identify the most effective solution for achieving interior thermal comfort. The green roof area in Taleb's study [34] was roughly 220 m2. Sprinklers were added to the green roof to enable evaporative cooling to ensure that the temperature of the roof remained cool even in the peak hours. The study proved that about 23.6% of the annual building's energy consumption was reduced when passive cooling strategies was used.

Furthermore, the use of natural ventilation for achieving indoor thermal comfort in Singaporean residential buildings has been examined by Liping and Hien [47]. The study found that by combining natural ventilation with intelligent facades [appropriate façade designs with efficient construction materials and shading devices] in residential buildings, thermal comfort can be improved while also conserving energy and ensuring sustainability. The predicted annual energy savings percentages were 73-77%, which is within the acceptable thermal comfort zone of 80% that is suggested by ASHRAE Standard 55. During the hours outside comfort zone, the study suggested using mechanical fan if needed to improve thermal comfort.

The study of Del Rio et al. [66] have employed a variety of different sorts of passive cooling approaches to improve the internal thermal comfort of a residential building in Japan during the hot-humid summer season. The approaches utilised in the study included an evaporative cooling louvre that was developed previously by Hirayama et al. [72] and reducing solar radiation by utilising vegetation and sunscreen to create a semi-outdoor space outside two windows of the house. The ideal ventilation settings to induce the cool air through the windows were then assessed. Figure [10] shows the evaporative cooling louvers that used in

Del Rio et al. [66] study. Table (1) summarised the studies that was conducted in the hot-humid climate and their conclusions.

Figure(10): Evaporative cooling louver
Source: [66]

Table(1): The studies that was conducted in the hot-humid climate and their conclusions.

Study	Climate	Methodology of the study	Conclusion
Mirrahimi et al. 2016 [31]	Tropical climate (Malaysia)	Review study	There is strong effect of different building components and reducing the energy that used for cooling
Bhikhoo et al., 2017 [32]	Tropical climate (Thailand)	Simulation study	Indoor overheating can be reduced when proper building design principles are used (roof materials and presence of balcony)
Husen and Mohamed, 2021 [21]	Tropical climate (Malaysia)	Review study and site observations	
Yusoff, 2020 [22]	Tropical climate (Malaysia)	Field measurement and numerical simulation.	Providing a confined area at the inlet may enhance indoor air velocity (the Venturi effect), thus enhancing the natural cross-ventilation in low-rise buildings located at the area where the wind speed is low.
Oleiwi & Mohamed, 2021 [23]	Tropical climate (Malaysia)	Simulation study	Protecting the building envelope by extending the overhang by 50% of its length enhanced indoor thermal

			comfort compared to other selected strategies.
Mohamed, 2020 [24]	Tropical climate (Malaysia)	Literature review and site observation	In traditional Malaysian mosques and Malay houses, there are at least 26 sustainable approaches which can be used as a starting point or guideline when designing new modern buildings in Malaysia, particularly those with passive design strategies.
Gamero-Salinas et al., 2021 [25]	Tropical climate (Tegucigalpa and San Pedro Sula in Honduras)	Simulation study	Natural ventilation, wall absorptance, the solar heat gain coefficient, and semi-outdoor spaces had the ultimate impact on overheating reduction
Al-Tamimi & Fadzil, 2011 [26]	Tropical climate (Malaysia)	Simulation study	Shading devices to minimise solar heat gain through building design.
Sulaiman, 2017 [27]	Tropical climate (Malaysia)	Experimental study	Using green façades can decrease air temperature inside the buildings.
Dahlan, 2011 [28]	Tropical climate (Malaysia)	Field measurement	The occupants perceived the thermal conditions in rooms that were shaded with a projected balcony (shading ratio of 0.9), a long roof overhang (shading ratio of 1.6) and an operable window-to-wall ratio of 0.3 to be thermally comfortable.
Nguyen, 2012 [29]	Tropical climate (Vietnam)	Simulation study	Natural ventilation strategies for windows opening is very effective cooling strategy. - Using bright colour for the exterior building envelope can improve indoor thermal comfort
Agung Murti Nugroho, 2007 [30]	Tropical climate (Malaysia)	Field measurement and CFD (Computational fluid dynamics) simulation software	Solar chimney can increase indoor thermal comfort and minimise energy consumption in single store terraced houses, while natural ventilation was not effective for this type of housing.
Tong et al., 2021 [33]	Tropical climate (Singapore)	Parametric study	Reducing façade's window-to-wall ratio also proved to have a

			good impact on deceasing indoor air temperature
Taleb, 2014 [34]	Dubai (hot-humid summer)	Simulation study	Energy saving can be achieved by using passive cooling strategies namely shading devices, double glazing, green roofs and using insulation.
Oleiwi & Mohamed, 2022 [35]	Tropical climate (Malaysia)	Simulation study	Protecting the windows from solar radiation by adding shading devices and closing the curtains resulted in good temperature reduction.
Lohia & Dixit, 2015 [37]	Scorching summers (India)	Field measurement	Double glazing is effective at reducing heat transmission inside buildings
Xamán et al., 2014 [38]	Hot- humid summer (Mexico)	Numerical study	Solar control film in a double glazed window can lower energy consumption
Al-Tamimi and Qahtan, 2016 [39]	Tropical climate (Malaysia)	Simulation study	Reflective double glazing can reduce indoor air temperature throughout the day, regardless of ventilation, with an optimal improvement of up to 107% and 14% in unventilated and ventilated rooms, respectively, when compared to single clear glazing.
Shen et al., 2011 [41]	Hot climate (China)	Experimental study	depending on location, season, and orientation, different coatings can reduce exterior and interior surface temperatures, and as a result, can reduce indoor mean radiant temperatures and energy consumption.
Wang et al., 2022 [42]	Hot climate (China)	Experimental study	Using Retro-reflective coatings can give better cooling potential than the Highly-reflective coatings in the high-density areas.
Cheikh and Bouchair, 2008 [43]	Hot climate (Algeria)	Experimental study	protecting roofs from solar radiation is necessary to avoid indoor overheating
Jaffal et al., 2012 [44]	Hot Summer (France)	Simulation study	With the addition of a green roof, the summer indoor air temperature was reduced by 2

			degrees Celsius, and the annual energy demand was reduced by 6%.
Dutta et al., 2017 [49]	Tropical climate (India)	Simulation study	In a tropical climate of the northern hemisphere, heat gain through south-facing windows is the greatest, followed by east, west, and north-facing windows
Mathew et al., 2022 [48]	Tropical climate (India)	Experimental study	Combining Polymer Dispersed Liquid Crystal (PDLC) glazing with southern and the northern windows' orientation for the tropical climate, energy consumption was the less
Sadafi et al., 2012 [51]	Tropical climate (Malaysia)	Case study	- Natural ventilation has achieved indoor thermal comfort for about 15 hours during the day for a terrace house. - Increasing air velocity by adding ceiling fan and reducing the absorption of radiant heat by adding shading devices can improve thermal comfort.
Kolokotroni et al., 2018 [54]	Tropical climate (Jamaica, Northeast Brazil and Ghana)	Experimental study	The usage of cool materials is most efficient in places with strong sun radiation and outside high air temperature.
Aldawi et al., 2013 [55]	Tropical climate (Australia)	Case study	Suggested new design wall systems that can increase indoor thermal comfort.
Latha et al., 2013 [58]	Tropical climate	Review study	using certain materials in the building envelope can improve thermal comfort, such as vacuum insulation panels (VIPs), phase change materials (PCMs), autoclaved cellular concrete (ACC), polymer skin, light-coloured external surfaces, reflecting paints, window treatments, and roof gardens.
Juarez, 2014 [50]	Tropical climate & Temperate climate	Simulation study	Thermal mass is effective in temperate climates, however, in a tropical climate, light weight design with minimal thermal mass is preferred.

Del Rio et al., 2019 [66]	Tropical climate (Japan)	Field measurement	Indoor cross ventilation can improve the internal thermal comfort.
Al-Tamimi, 2015 [67]	Tropical climate (Malaysia)	Field measurement	Natural ventilation can improves indoor environmental performance by 80% and 50% during the day and night, respectively.
Oleiwi, 2020 [68]	Tropical climate (Malaysia)	Simulation study	Applying night ventilation can keep the indoor space within the comfortable temperature
Daghih et al., 2012 [69]	Tropical climate (Malaysia)	Field measurement	The office that have a combination of windows-door opening performed better in terms of air exchange rate, age of the air and air efficiency than the opening closed office
Jamaludin et al., 2014 [53]	Tropical climate (Malaysia)	Field measurement	Night ventilation is the best method, followed by daytime ventilation, and then, full-day ventilation.
Liping and Hien, 2007 [47]	Tropical climate (Singapore)	Model	Combining natural ventilation with intelligent facades can improve thermal comfort can and reduce energy consumption.

3. Conclusion

As a part of the movement toward green sustainable building, passive cooling solutions have earned high attention as an alternative method of cooling and ventilating indoor spaces. This paper reviewed different types of passive cooling solutions that can be adopted in the hot-humid climates as means of preventing overheating, decreasing indoor temperature and reducing energy usage by dividing them into three main categories. The first category depends on protecting the building from solar radiation such as using shading devices. The second category of passive cooling depends on controlling thermal storage capacity of building structure such as using high thermal mass materials. The third category depends on heat dissipation such as applying natural ventilation and using radiative cooling.

Many researches have been conducted to emphasise the importance of employing passive cooling solutions to improve thermal comfort inside buildings. This research leads the way for choosing the optimum passive cooling approaches for achieving indoor thermal comfort and energy savings in hot and humid climate. The study concluded that protecting the buildings from direct solar radiation, such as using shading devices, doubling the glazing and applying solar reflective film for the windows, closing the curtains, coating the building with light colour and high reflective materials, using different types of vegetation, installing the appropriate sort of insulation, selecting the best orientation for the building and its openings and using proper construction materials are effective in the hot-humid climate. In addition, applying natural night ventilation by opening the windows during the night was proved as an effective strategy in this climate region. However, using high thermal mass or radiant cooling is not recommended for the hot-humid climate. The study emphasised the need of considering the appropriate passive cooling strategies for the hot- humid climate to reduce energy consumption in this region. It is recommended to study other types of passive cooling strategies in different types of climates to highlight the most preferable passive cooling strategies for each type of climate.

List of abbreviations.

List of abbreviations	
ACC	Autoclaved Cellular Concrete
CFD	Computational Fluid Dynamics
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
HR	Highly-reflective
IES-VE	Integrated Environmental Solutions-Virtual Environment
PCMs	Phase Change Materials
PDLC	Polymer Dispersed Liquid Crystal
RR	Retro-Reflective
VIPs	Vacuum Insulation Panels

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