Thermal resilience in schools – Literature review of heatwave adaptation solutions

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Abstract - In France, schools and their 12 million students and 854,000 teachers face particular thermal discomfort during academic periods. Schools are particularly vulnerable to increasing temperatures due to the young age of occupants, high occupancy densities and limited possibilities for behavioral adjustments to improve thermal comfort. Thermal resilience studies need effective cooling techniques and consideration of future climate. This article presents a first step in this work. Different passive and active cooling strategies used in schools and described in the scientific literature will be analyzed here.

1. Introduction

Heatwaves significantly disrupt learning environments such as schools[1]. Increasing temperature results in reduced memory retention, attention, and problem-solving abilities. As the study of Goodman et al. [2] indicates, a 0.56°C temperature increase in the average school-year temperature can reduce annual learning gains by approximately 1%. Consequences of heatwaves on schools are particularly significant in urban areas like Paris, where the urban heat island effect (UHI) exacerbates already high temperatures [3]. High occupant density, while students' adaptability to varying temperatures is constrained by limited options available to them, makes it challenging to maintain thermal comfort and build thermal resilience [4]. Thermal resilience refers to the ability of school buildings to maintain indoor comfort conditions regardless of external climate changes [5]. To address those challenges, various strategies, ranging from purely passive approaches to active systems, have been developed to mitigate heat stress in buildings [6]. The objective of our work is to review heat mitigation strategies reported in the scientific literature and tailored specifically for school environments.

2. Methodology

A comprehensive literature review focused on peer-reviewed journals and conference proceedings available through reputable academic databases such as Google Scholar, ScienceDirect, and ResearchGate. Keyword searches were utilized to identify relevant studies on cooling strategies for schools. Citation tracking and reference mining were employed to ensure the inclusion of the most recent and impactful research. The literature review encompassed studies from various countries and climatic contexts, including direct research on schools in France, Italy, the United Kingdom, Chile, Brazil, India and South Asia, Cyprus, Greece, Palestine, Burkina Faso, Sweden, and Canada. The studies employed diverse methodologies, with the majority utilizing simulation and modeling (60%), followed by monitoring and field measurements (40%), experimental testing (20%), case study analyses (22%), and surveys (18%).

3. Heat mitigation methods: Classification and Effectiveness

Heat mitigation strategies can be categorized based on their functional roles in maintaining indoor thermal comfort. In this paper, the structured classification draws from established

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methodologies in passive cooling research outlined by Tavakoli et al 2022 [6]. Those are categorized into 3 main types: **Prevention**, which restrict heat entry; **Dissipation**, which concentrated on removing heat; and **Modulation**, which corresponds to strategies that regulate heat absorption, storage, and release over time. Table 1 gives the overview of all studies included in the review, and subsequent paragraphs give more details on main strategies.

Classification	Methods	Details						
Prevention	Insulation and Building Envelope	insulation [5], [7], [8], [9], [10]						
	Glazing and Shading	Double glazing (different types) [8],[13],[14],[15]	Triple glazing [14], [15]	Coating and solar protection [13],[17]	Smart glazing [18]	External and Internal shading [19],[9], [20]	Fixed and Moveable shading [5]	Shading angles [15]
	Reflective Materials	Roof coating (reflective, white, super cool) [13],[21],[22],[8]						
	Vegetation and Cooling	Green roof [13], [23]	Green façade [24]	Courtyard [25],[26]				
Dissipation	Ventilation methods	Opening windows [23],[4]	Cross/single side ventilation [29]	Night ventilation [5],[17], [20],[27],[9]				
	Evaporative cooling	Direct/Indirect evaporative cooling [6],[30]						
	Ground-based cooling	Buried (earth) ducts [13],[31]	Canadian well [32]					
Modulation	Mechanical ventilation systems and HVAC control	Optimized HVAC system [34],[35]	Mechanical ventilation and heat recovery [5]					
	Thermal modulation material	Thermal mass [13],[14],[27]	Phase Changed Materials (PCMs) [29],[18]					
	Thermal adaptive envelope system	Trombe wall [13],[36],[10]						
	Renewable energy integration	PV [37],[38]						

Table 1: *Heat mitigation strategies classification*

3.1. Prevention

Prevention strategies aim to restrict heat entry into school buildings.

2.1.1 Insulation and Building envelope

Having used insulation improvements in walls, ceilings, roofs, and external facades considerably decreases heat transfer. Several studies had been conducted to show the effect of the insulation to reducing the heating demands [5], [7], [8]. Researchers [9], [10] observed that roof and wall insulation effectively reduce cooling demands—by respectively up to 14.2% and 6.7%. However, despite the effectiveness of various types of insulation in reducing heating demand, they can pose challenges during the summer. In particular, they may inadvertently increase cooling requirements under certain conditions. For instance, for future climate, floor insulation can have the opposite effect, having overheating and increasing cooling needs due to its impact on thermal retention during warmer months [5], [11]. To prevent overheating, insulation should be implemented combined with adaptive ventilation solutions [12].

2.1.2 Glazing and Shading

The installation of energy-efficient windows is emphasized as a crucial strategy for minimizing heat gains during the cooling period. Technologies such as low thermal transmittance windows [13], solar protection glazing [13], argon-filled double glazing [8], [14], [15], double low-e [15], [16], double solar control [16] , triple-glazing [14], [15], using low-e coating or film on the outside of classroom windows [17] and electrochromic glazing [18] offer an excellent foundation for improving thermal comfort and reducing energy demands in educational settings. However, using these technologies, is not sufficient to obtain the best condition of thermal resilience in classrooms and it should be combined with shading devices.

External shadings are installed outside the building and are highly effective in reducing solar heat gain. They can lower cooling loads by up to 40% and are particularly beneficial in mixed humid climates, where they can completely eliminate overheating in some cases [19]. Zinzi et al.[9] indicate that in Italian schools the installation of the external shading devices could reduce the temperature of classrooms by up to 2-3°C. Also, it has been shown that internal shading devices reduce overheating hours by about 57% in mixed humid climates [9], [20].

Movable shading devices complement fixed shadings by addressing seasonal variations in solar gains. Heracleous et al.[5] studied fixed and moveable shading devices for schools in Cyprus. They concluded that fixed solar shading could be beneficial during summer to reduce overheating. However, they may cause problems in winter by blocking beneficial solar gains, thus increasing heating demand.

In addition, the orientation of shading devices plays a critical role in optimizing their impact on cooling energy demands. Jaouaf et al. [15] studied vertical (VSA) and horizontal (HSA) shading angles. Lower VSA means that the shading device is positioned closer to the vertical plane, which effectively blocks more direct sunlight from entering the building. So, lower VSA is more beneficial as it correlates with reduced cooling energy demands, while HSA has a minimal impact on cooling efficiency.

2.1.3 Reflective materials

Applying reflective coatings on building surfaces effectively reduces solar energy intake. López et al. [13] suggested reflective roof as one of the passive cooling strategies in schools, that not only is cost effective and environmentally friendly, but also contributes to energy efficiency by reducing cooling energy demand and mitigating UHI. Reflective roof coatings can decrease discomfort hours by 30% in hot dry, 2.3% in very hot dry, and 1.9% in extremely hot dry climates [21]. In mixed humid climates, increasing roof reflectivity reduces overheating by up to 89% in poorly insulated buildings and 27% in well-insulated ones. Also, white roof coatings can lower overheating hours by 34% in such regions [22]. Azevedo Correia et al. [8] also emphasize the effectivity of super cool coatings on the roofs and on the envelope in Brazilian schools. Super cool roofs and envelopes are designed to reflect more sunlight, absorb less heat and with their high emissivity, efficiently release the absorbed heat back to the atmosphere.

2.1.5 Vegetation and Cooling

Vegetation-based cooling strategies are diverse and can be applied across different architectural elements, including roofs, facades, and courtyards. Green roofing has increasingly established itself as an important element in the strategies of nature-based solutions. Allowing the vegetation to grow on the roof mitigate the heat flux through the roof by shading the roof surface with plants, evapotranspiration of the plants, and the additional thermal insulation and mass [13], [23].

Plant characteristics play a vital role in optimizing thermal performance when vegetation-based cooling strategies are applied in different climates. Based on the findings of Mahmoodzadeh et al.'s research [24], vegetation in North American school buildings offers multifaceted benefits, impacting both cooling and heating loads while improving thermal comfort. Key plant characteristics such as leaf area index (LAI), plant height, stomatal resistance, albedo, and emissivity significantly influence energy performance. Low stomatal resistance enhances evapotranspiration, cooling the surrounding air, while plants with high albedo reflect solar radiation, lowering soil temperatures. High LAI and taller plants provide extensive shading, reducing soil surface temperatures and cooling loads. However, in heating-dominated climates, taller plants might increase heating loads by limiting solar absorption.

Vegetation in outdoor spaces also provides substantial cooling benefits, particularly when trees are positioned strategically near building walls. Berry et al. [25] indicates that tree shade lowered the temperature of the outside air by up to 1°C and the temperature of the wall surface by up to 9°C. The tall trees lost their cooling benefits when they were moved farther away from the building wall, and the smaller trees had no effect in lowering the surface temperatures of the external walls. Furthermore, Salameh et al. results [26] shows that in hot arid climate, vegetation in courtyards lowered Predicted Mean Vote (PMV) values from "hot" to "warm," highlighting the substantial effect of greenery on outdoor comfort.

Reflective materials, combined with vegetation, further enhance cooling by reducing solar heat gain. High-albedo materials significantly reduce solar heat gain by reflecting sunlight, which decreases the cooling load on buildings [27]. Studies [27],[28] show that plant albedo, along with the reflective properties of roofs and walls, can lower indoor temperatures by 2°C to 5°C, depending on the extent of coverage and local climatic conditions.

3.2. Dissipation

Dissipation strategies aim to remove accumulated heat from buildings, ensuring thermal comfort and reducing energy demands.

2.2.1 Ventilation Methods

Natural ventilation through windows remains a primary strategy for managing indoor temperatures in classrooms. Cascone et al.[23] discussed the use of natural ventilation through opening windows and emphasized the importance of strategic window opening to manage solar gain and improve thermal comfort. While opening windows can reduce overheating, it may not be sufficient to meet all thermal comfort needs. Lala et al. [4] conducted a survey across multiple cities in India regarding the impact of heatwaves' on students. In very hot conditions, all teachers (100%) admitted to opening doors and windows and adjusting the speed of fans to help in controlling the temperature inside classrooms. Although 79% of teachers stated that windows were opened every day, 96% felt classrooms were not well-ventilated.

Cross-flow and single-sided ventilation are indeed natural ventilation strategies that offer targeted solutions to mitigate overheating. Davidson et al. [29] proposed these methods , to mitigate overheating of the higher education under future climates. Cross-flow ventilation promotes air movement across a space, enhancing circulation and cooling efficiency. Single-sided ventilation, with airflow limited to one side, is less effective and better suited for spaces where cross-flow ventilation is not feasible. Another strategy to enhance natural ventilation is ventilated roof which are designed to allow air to flow between the roof layers.

In general, night ventilation proves to be a critical passive cooling strategy for mitigating overheating in educational buildings. In Cyprus [5], employing night ventilation can reduce cooling degree hours by 62% in a typical meteorological year. In the UK [17], [20] while external temperature drops significantly overnight, the benefit of night ventilation is sometimes restricted by sealed façades. However, its effectiveness increases substantially when combined with measures like window overhangs (shadings), which enhance thermal comfort and reduce dependency on mechanical cooling. Similarly a study in Poland [27] indicated that night ventilation has superior impact on summer thermal comfort compared to other methods such as ground-air heat exchangers. An application in Milan [9] highlights that the night ventilation results in significantly lower overheating risks compared to the baseline scenario, with operative temperatures exceeding 26°C and 28°C in only 2% and 20% of occupancy hours, respectively.

2.2.2 Evaporative Cooling

Evaporative cooling has been proposed by Tavakoli et al.[6] as a method of achieving indoor thermal resilience for non-residential buildings, citing two different approaches: direct and indirect evaporative cooling . Noting that, Future climate conditions might be drier than present. Thus, in the future, in current mixed humid climatic regions, evaporative cooling could be advantageous. In Direct Evaporative Cooling (DEC), the reduction in dry bulb temperature of the air with an increase in its humidity happens with the direct contact of water with the air stream. In summer, DEC can achieve energy savings of up to 82% compared to conventional air conditioning systems [30]. However, since this method increases the humidity, this is not the best option for humid climates. Indirect Evaporative Cooling (IEC) addresses the humidity issue by using two separate air streams, preventing direct contact between water and the air being cooled [30].

2.2.3 Ground-Based Cooling

Among passive cooling techniques, using lower ground temperature through some heat exchangers provides a reliable option for reducing cooling loads and stabilizing indoor temperatures [13]. Based on the study of Monna et al. [31] a buried (earth) duct system in combination with the solar chimney works effectively by stabilizing indoor temperatures of Palestine's school. Results indicate that on days with outdoor temperatures > 25ºC, almost all the classrooms' temperature is 5ºC lower than the outside.

For year-round temperature control, Canadian wells provide an alternative passive strategy. In this system, the outdoor air is naturally precooled to 16–18 °C (and preheated in winter) through the Canadian well before it is entered into the building, resulting in reducing the reliance on active cooling systems and ensuring consistent indoor thermal conditions [32].

3.3. Modulation

Modulation strategies regulate heat absorption, storage, and release, enhancing the thermal environment by dynamically balancing energy use and comfort.

2.3.1 Mechanical Ventilation Systems and HVAC control

Mechanical ventilation and HVAC systems play a pivotal role in ensuring thermal comfort and energy efficiency in educational buildings. Mechanical ventilation fits dissipation when expelling heat, like exhaust fans, and modulation when actively regulating indoor conditions, like heat recovery systems. Heracleous et al. [5] proposed mechanical ventilation with heat recovery to reduce cooling demand in Mediterranean schools. Some studies [5], [33] use mix-mode, which combine natural and mechanical ventilation methods, as an effective strategy, especially for adapting to variable climates.

By implementing new control strategies, such as those based on occupancy and environmental conditions, the HVAC system can more effectively manage cooling demand [34]. The study of Englund et al. [34] suggests that in Swedish schools, switching from a constant air volume (CAV) system to a variable air volume (VAV) system, which adjust airflow based on need, can significantly reduce cooling demand. Also, smart HVAC control strategies further enhance energy efficiency by dynamically optimizing system performance. Cho et al. [35] proposed an intelligent HVAC control strategy for supplying comfortable and energy-efficient school environment. Under the non-disturbance scenario, the proposed strategy consumed 870 kWh for cooling, which represent 84% of the energy consumption compared to a rule-based algorithm.

2.3.2 Thermal modulation materials

Walls, floors and roofs with high thermal inertia play a crucial role in mitigating overheating risks. During summer, these construction systems can absorb heat during the day and release it at night, allowing night ventilation to expel the accumulated heat and prepare the system for the next day. This ability to store, conserve, and gradually release heat reduces the reliance on mechanical heating and cooling systems, creating a thermally resilient building envelope optimized for year-round comfort. Integrating such systems with effective ventilation further enhances their performance, making them a vital part of sustainable thermal design [13]. A study in Nepal's schools by Moktan et al. [14] indicates that using cast concrete with a thickness of 300 mm as thermal mass in external walls reduced classroom temperatures by approximately 3°C during midday peaks compared to the base case model. Dudzińska et al. [27] observed the effect of thermal mass and passive cooling methods. It is reported that having thermal mass and night ventilation led to reduce peak indoor air temperatures by approximately 3.9°C, ensuring better conditions during hot days. Using thermal mass combined with passive cooling methods could decrease up to 30% of discomfort hours in schools.

To address the issue of overheating, further analyses are planned to examine how thermal mass affects microclimate parameters and how different comfort models influence the assessment of conditions in overheated passive buildings [29]. addition to the passive thermal mass, Phase Change Materials (PCMs) are recognized for their ability to stabilize indoor temperatures, especially in regions with high diurnal temperature variations. Their effectiveness is strongly influenced by the selection of appropriate melting points, which must align with local climatic conditions to ensure optimal thermal buffering [18]. Camacho-Montano et al.[18] demonstrate that PCMs as the internal partitions have potential of reducing discomfort hours due to overheating by up to 23 hours in lightweight building types.

2.3.3 Thermal adaptive envelope systems

Trombe walls offer a passive solution for both heating and cooling applications in schools [13]. In hot-arid climates, Rabani et al. [36] found that integrating Trombe walls with solar chimneys and evaporative cooling systems reduced by 8°C the indoor temperatures. In addition, energy efficiency was improved by 30%. Shen et al. [10] used porous materials for evaporative cooling and natural ventilation and reduced indoor temperatures by up to 14°C while improving the airflow.

2.3.4 Renewable Energy Integration

Renewable energy systems further enhance thermal modulation. Sun is the most important resource which could be used for cooling approaches in schools, as the peak solar radiation is in general aligned with high cooling needs. Heracleous et al. [37] demonstrated that a Solar PV systems' energy production could met the energy needs, including cooling demand, of retrofitted school in Mediterranean climate. Moreover, Sun K. et al [38] . revealed that PV systems (supplying 50 % of the HVAC needs) and thermal energy storage improve resilience against climate change impacts such as heat waves.

4. Conclusion

In this paper, various strategies to address the challenge of overheating in schools have been explored and categorized into three main approaches: prevention, dissipation, and modulation. Each of these approaches offers distinct advantages depending on the climate conditions and the construction characteristics of the building. A key finding from this study is that combining multiple strategies is often more effective than using them individually. For example, integrating insulation with ventilation, or utilizing night ventilation alongside shading significantly enhances thermal comfort and energy efficiency. To design retrofitted schools capable of managing overheating, it is recommended to apply all three categories of strategies in a complementary manner. Prevention strategies should be used to minimize heat gain, dissipation methods to remove excess heat, and modulation techniques to regulate indoor temperatures effectively. This integrated approach ensures a more resilient, comfortable, and sustainable building design.

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