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Review article

Passive Cooling Strategies in Institutional Buildings: A Systematic Review of Thermal Comfort Performance and Energy Reduction Potential

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ABSTRACT

Institutional buildings such as schools, universities and public facilities often depend on mechanical cooling despite constrained energy budgets. This review examined how passive cooling strategies can reduce cooling demand while maintaining acceptable indoor conditions. Searches conducted between April and May 2026 used ScienceDirect, Wiley Online Library, SpringerLink, Taylor & Francis Online and Google Scholar, supplemented by backward and forward citation tracking. Twenty-five publications were retained for qualitative evidence mapping. Because the corpus contained both primary empirical studies and secondary reviews or conceptual sources, the revised synthesis separates these evidence types: primary empirical studies inform direct outcome synthesis, while secondary sources provide taxonomy, context and interpretation. The clearest directly traceable energy result in the primary institutional evidence was an 18–33% annual primary-energy saving from natural ventilation in Spanish school buildings. Adaptive-comfort evidence also indicates that occupants of naturally ventilated educational buildings may accept conditions around 1–2°C beyond static-model expectations, although the magnitude varies by climate, method and building operation. The literature remains geographically uneven and methodologically heterogeneous, with limited long-term field monitoring and lifecycle-cost evidence. These limitations mean that passive strategies should be interpreted as climate- and context-dependent rather than as universal effect sizes.

KEYWORDS

passive cooling; institutional buildings; thermal comfort; energy efficiency; natural ventilation; solar shading; adaptive comfort; systematic review

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1. INTRODUCTION

Institutional buildings such as schools, hospitals and government offices often have demanding indoor-environment requirements. They can accommodate large numbers of occupants for extended periods and may require reliable ventilation and temperature control. In warm climates, these conditions can make cooling a substantial component of building energy use. Earlier work on building envelopes identified cooling as a major concern in warm regions (Sadineni et al., 2011), while broader passive-cooling literature has emphasised the growing challenge of cooling demand under rising outdoor temperatures (Santamouris, 2017). For public institutions, the issue is also financial because expenditure on electricity and air-conditioning maintenance can compete with other service priorities.

Passive cooling seeks to limit unwanted heat gains or remove heat through building form, materials and natural environmental processes rather than relying solely on compressor-based cooling. Common approaches include natural ventilation, external shading, reflective surfaces, insulation, thermal mass, evaporative cooling and phase-change materials. Their performance depends strongly on climate, building geometry, occupancy and operation.

Thermal comfort is equally important. Energy savings are not useful if occupants experience persistent discomfort or unacceptable indoor air quality. Adaptive-comfort research recognises that clothing, air movement, window use, expectations and recent outdoor conditions influence thermal perception. Educational-building studies therefore provide an important test of whether static comfort models are sufficiently representative for naturally ventilated institutions.

Several existing reviews overlap with parts of this topic, but their objectives differ from the present synthesis. Sadineni et al. (2011) review building-envelope components across building types; Santamouris (2017) provides a broad taxonomy of passive cooling; Zomorodian et al. (2016) focus on thermal comfort in educational buildings; Jia et al. (2021) examine the interaction between thermal comfort, indoor air quality and ventilation energy in educational settings; and Hu et al. (2023) review passive design primarily in residential

buildings in hot climates. The present review adds value by linking passive strategy, thermal-comfort outcomes, energy outcomes and climate context specifically for institutional applications, while explicitly separating primary empirical evidence from secondary review material to avoid double-counting.

The review addresses three questions: (1) which passive cooling strategies have been examined in institutional buildings; (2) what thermal-comfort and energy outcomes have been reported; and (3) what climatic, geographic and methodological gaps remain? The aim is not to identify a universal effect size, but to clarify the circumstances in which particular passive measures appear useful and the strength of the evidence supporting those conclusions.

2. LITERATURE REVIEW

2.1 Passive Cooling: Principles and Taxonomy

Passive cooling controls heat gain, storage and removal with little or no direct mechanical energy. Santamouris (2017) groups passive approaches according to whether they limit heat entry, modify heat storage or reject heat to an available sink. Shading, insulation and reflective surfaces mainly reduce heat gain; thermal mass and phase-change materials alter heat storage; and ventilation, evaporation and earth coupling support heat rejection. In practice, these mechanisms often interact, so combinations may be more useful than isolated measures.

The building envelope is central because roofs, walls, windows and openings regulate conductive, radiative and airflow exchanges. Sadineni et al. (2011) show that envelope choices can materially affect building energy demand. More recent envelope reviews also discuss switchable glazing, thermochromic materials and radiative cooling (Kitsopoulou et al., 2024), although much of that literature is not specific to institutional buildings.

2.2 Thermal Comfort in Institutional Environments

Institutional environments present a distinctive comfort problem. Classrooms can have high internal gains because many occupants share a relatively small space, while students and patients may have limited ability to leave or adjust environmental controls. Zomorodian et al. (2016) found that educational-building comfort studies frequently diverge from predictions based on conventional office-oriented models.

Field evidence supports the use of adaptive interpretation in naturally ventilated schools. Hwang et al. (2009) reported Taiwanese school responses that departed from static-model expectations; the reviewer-verified comparison supports a difference of roughly 1–2°C rather than the 1–3°C previously stated. De Dear et al. (2015) also documented adaptive behaviour among Australian schoolchildren, while López-Pérez et al. (2019) developed an adaptive model for educational buildings in a hot-humid climate. These studies support a broader interpretation of comfort, but they do not justify a universal temperature offset across all climates or institutions.

Comfort must also be interpreted alongside indoor air quality. Jia et al. (2021) describe a recurring interaction between thermal comfort, ventilation energy and air quality in educational buildings. Increasing ventilation may improve perceived freshness and pollutant dilution, but it can also increase thermal loads when outdoor conditions are unfavourable.

2.3 Natural and Hybrid Ventilation

Natural ventilation is one of the most frequently examined passive approaches in the institutional literature. Its performance depends on pressure differences, opening design, external conditions and occupant operation. Gil-Baez et al. (2017) reported annual primary-energy savings of 18–33% in Spanish school buildings when a natural ventilation system replaced mechanical ventilation while classroom comfort was maintained. Huang and Hwang (2016) compared natural, hybrid and air-conditioned operation in Taiwanese schools and showed that building design and operating mode materially influence both cooling energy and overheating risk.

Anuja and Amutha Priya (2019) investigated natural-ventilation use in an Indian institutional building using airflow-related calculations and a questionnaire of 200 occupants. The paper supports conclusions about ventilation satisfaction and operational opportunities, but it does not support the 30–50% energy-saving range attributed to it in the previous manuscript. That numerical claim has therefore been removed.

2.4 Solar Shading and Daylighting

Solar control reduces cooling demand by limiting direct solar gains before they enter the occupied space. Tzempelikos and Athienitis (2007) modelled the interaction between glazing, shading and lighting demand, demonstrating the need to optimise cooling and daylighting together. Kim and Kim (2010) similarly evaluated an external shading configuration using simulation and measurement. These studies support the direction of the effect, but the revised review does not assign a single percentage saving unless the value is directly traceable to the original study.

In schools, daylighting must balance visual quality, electric-lighting demand and solar heat gain. Pellegrino et al. (2015) combined field measurements with climate-based simulation in classrooms to assess daylighting performance as part of green-school retrofit. Ragab et al. (2025) showed that window configuration and timed cross-ventilation can influence air quality and thermal comfort in an arid educational building.

2.5 Building Envelope and Emerging Technologies

Envelope measures such as insulation, reflective surfaces and thermal storage can reduce or delay heat gains. Synnefa et al. (2007) demonstrated that cool-coloured coatings can reduce surface temperatures, although that study is not institution-specific. Reviews of phase-change materials and passive envelopes provide useful technological context (de Gracia & Cabeza, 2015; Kitsopoulou et al., 2024), but they are treated as secondary evidence in this review rather than as primary data points in quantitative ranges.

3. METHODOLOGY

3.1 Framework and Protocol

The review was reported with reference to PRISMA 2020 (Page et al., 2021). Review questions, search terms, eligibility criteria and extraction fields were defined before synthesis. No prospective protocol registration was completed. PROSPERO was not used because it is primarily a registry for systematic reviews with health-related outcomes, whereas this review concerns building-science and energy-performance evidence. The absence of a prospectively registered protocol is nevertheless acknowledged as a limitation because registration in a suitable open repository could have strengthened transparency.

3.2 Search Strategy and Information Sources

Searches were conducted between April and May 2026 using ScienceDirect, Wiley Online Library, SpringerLink, Taylor & Francis Online and Google Scholar. These are described here as search platforms and information sources rather than as five equivalent bibliographic databases. Search strings combined terms for passive cooling strategies, institutional or educational buildings, thermal comfort, ventilation, cooling load and energy performance. Reference lists were examined and forward and backward citation tracking was used to identify additional relevant publications.

Scopus and Web of Science were not searched in the original review. This is a limitation because the four publisher platforms have source-specific coverage and Google Scholar has broad but non-fixed indexing that is less reproducible than curated citation databases. The review may therefore have missed relevant studies indexed outside the searched platforms. Future updates should include Scopus and/or Web of Science and report the complete reproducible search strings for each source.

3.3 Eligibility Criteria

Publications were eligible for evidence mapping when they addressed at least one passive cooling strategy relevant to public, educational or other institutional buildings and reported or synthesised thermal-comfort, indoor-environment or energy outcomes. English-language peer-reviewed publications were considered. Residential-only studies and general building studies were not treated as direct institutional evidence; where retained for technological context, they were classified as secondary/contextual sources and excluded from direct quantitative synthesis. Conference papers, theses, non-peer-reviewed grey literature and simulation studies without meaningful validation or institutional relevance were excluded from direct synthesis.

3.4 Selection and Screening

The original search identified 101 records. After removal of three duplicates, 98 records underwent title and abstract screening. Fifty-five records were excluded at that stage. Forty-three full texts were assessed, of which 18 were excluded for insufficient institutional relevance, missing essential comfort or energy outcomes, or inadequate validation. Twenty-five publications were retained for qualitative evidence mapping. During revision, the unit of synthesis was clarified: 15 publications were treated as primary empirical evidence and 10 as secondary or contextual evidence. Secondary sources were not used to generate pooled or headline percentage ranges.

Independent duplicate screening and extraction were not documented in the materials available for this revision. The manuscript therefore does not claim that two reviewers independently screened, extracted or appraised every record.

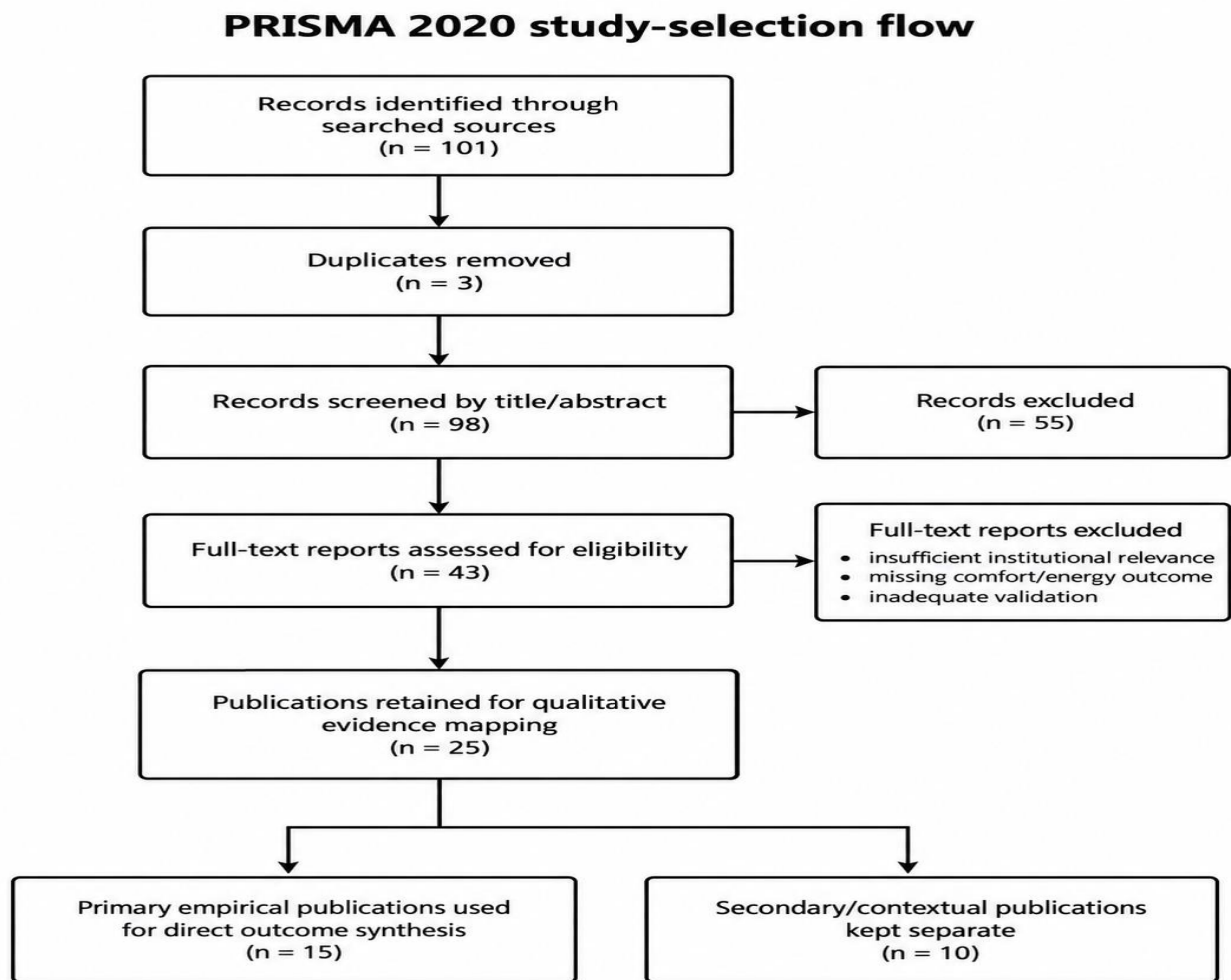


Figure 1. PRISMA 2020 study-selection flow

3.5 Data Extraction and Synthesis

Data extraction covered author, year, location, climate, building type, passive strategy, study design and reported thermal-comfort, indoor-environment and energy outcomes. Because the included literature comprised different study designs and outcome measures, a uniform numerical quality-scoring system was not

applied across the corpus. Instead, the synthesis distinguished studies according to their design, institutional relevance, validation and evidence type. Primary empirical studies formed the basis of direct outcome synthesis, while reviews, meta-analyses and conceptual publications were used to provide technological context, interpret broader patterns and identify research gaps. Statistical meta-analysis was considered inappropriate because study designs, climatic conditions and reported outcomes were highly heterogeneous. Direct numerical statements were therefore restricted to outcomes that could be traced to individual primary empirical studies. Secondary publications were not combined with primary studies to generate pooled percentage ranges.

4. RESULTS AND DISCUSSION

4.1 Composition and Unit of Synthesis

The evidence map contains 25 publications, but they do not represent 25 independent primary datasets. Ten are reviews, meta-analyses or conceptual/contextual works and 15 are primary empirical publications. This distinction is critical because combining secondary reviews with primary studies in the same percentage range can count the same underlying evidence more than once. Table 1 therefore identifies the evidence type and synthesis role explicitly.

Table 1. Characteristics and evidential roles of publications included in the synthesis

Source	Year	Context	Focus	Design	Role in synthesis
Anuja & Amutha Priya	2019	India	Institutional natural ventilation	Field calculations + questionnaire	Primary; direct qualitative synthesis
Chow et al.	2013	Hong Kong	Daylighting controls	Field/simulation	Primary; contextual because not institution-specific
de Dear & Brager	1998	International	Adaptive comfort	Field-database analysis	Primary foundational evidence
de Dear et al.	2015	Australia	Adaptive comfort in schools	Field survey	Primary; direct synthesis
Gil-Baez et al.	2017	Spain	Natural ventilation in schools	Experimental + simulation	Primary; direct quantitative synthesis
Heracleous & Michael	2019	Eastern Mediterranean	Natural ventilation in education	Field + simulation	Primary; direct synthesis
Huang & Hwang	2016	Taiwan	Natural/hybrid ventilation in schools	Parametric analysis	Primary; direct synthesis
Hwang et al.	2009	Taiwan	Adaptive comfort in schools	Long-term field survey/statistics	Primary; direct synthesis
Kim & Kim	2010	South Korea	External shading	Measurement + simulation	Primary; contextual strategy evidence
López-Pérez et al.	2019	Mexico	Adaptive comfort in education	Field study	Primary; direct synthesis
Pellegrino et al.	2015	Italy	Daylighting in schools	Field + simulation	Primary; direct synthesis
Ragab et al.	2025	Egypt	Window design/ventilation	Experimental + simulation	Primary; direct synthesis
Samani et al.	2016	Portugal	Passive cooling	Experimental/simulation	Primary; contextual, not institutional

Source	Year	Context	Focus	Design	Role in synthesis
Synnefa et al.	2007	Greece	Cool coatings	Experimental	Primary; contextual, not institutional
Tzempelikos & Athienitis	2007	North America	Shading control	Simulation/optimisation	Primary; contextual, not institutional
Ameen et al.	2026	International	Ventilation in NZEBs	Invited review	Secondary/contextual only
Amer et al.	2015	International	Evaporative cooling	Review	Secondary/contextual only
de Gracia & Cabeza	2015	International	Phase-change materials	Review	Secondary/contextual only
Hu et al.	2023	Hot climates	Passive design, residential	Systematic review	Secondary/contextual only
Jia et al.	2021	International	Comfort-IAQ-energy in education	Comprehensive review	Secondary/contextual only
Kitsopoulou et al.	2024	International	Passive envelope technologies	Review	Secondary/contextual only
Nicol & Roaf	2012	International	Adaptive comfort	Conceptual/chapter	Secondary/contextual only
Sadineni et al.	2011	International	Building envelope	Review	Secondary/contextual only
Santamouris	2017	International	Passive cooling taxonomy	Review chapter	Secondary/contextual only
Zomorodian et al.	2016	International	Thermal comfort in education	Review	Secondary/contextual only

4.2 Thermal Comfort Performance

The direct institutional field evidence consistently supports adaptive interpretation of thermal comfort, but the magnitude is not uniform. Hwang et al. (2009), de Dear et al. (2015) and López-Pérez et al. (2019) show that occupants in naturally ventilated educational buildings can report acceptable conditions outside ranges predicted by static models. The headline statement has therefore been revised from 1–3°C to approximately 1–2°C, consistent with the specific Hwang et al. comparison identified by the reviewer. This value should be read as study-specific evidence rather than a universal institutional comfort allowance.

Ragab et al. (2025) reported that timed cross-ventilation in an arid educational setting reduced indoor temperature by about 1–2°C and lowered carbon-dioxide concentration by 36%, while acceptable PMV values were maintained for 40% of classroom hours. These results illustrate why ventilation performance should be interpreted across thermal comfort and indoor air quality rather than temperature alone.

4.3 Energy Reduction: Primary Evidence Only

The previous headline range of approximately 9–62% has been removed because its lower bound was not traceable to Table 4.3 and its upper bound was drawn from a source that is a review rather than an independent school simulation. The revised synthesis does not combine secondary reviews with primary studies to construct an overall percentage range.

Among the directly traceable primary institutional evidence, Gil-Baez et al. (2017) reported annual primary-energy savings of 18–33% for natural ventilation compared with mechanical ventilation in school buildings while maintaining classroom comfort. Other primary studies in the corpus report beneficial energy, cooling-load, daylighting, surface-temperature or comfort outcomes, but their metrics and baselines are too

heterogeneous to support a single pooled percentage range without extracting comparable values directly from each original article.

Table 2. Traceable passive-cooling outcomes from supporting primary studies

Strategy/evidence	Supporting primary study	Traceable outcome used	Interpretation
Natural ventilation in schools	Gil-Baez et al. (2017)	18–33% annual primary-energy saving	Direct primary institutional evidence; used quantitatively
Natural/hybrid ventilation	Huang & Hwang (2016)	Energy and overheating performance compared across modes; no pooled percentage used here	Direct primary institutional evidence; narrative synthesis
Institutional natural ventilation	Anuja & Amutha Priya (2019)	Occupant satisfaction and airflow/ventilation assessment; no 30–50% energy-saving claim retained	Direct primary institutional evidence; narrative synthesis
External shading/daylighting	Kim & Kim (2010); Tzempelikos & Athienitis (2007); Pellegrino et al. (2015)	Positive energy/daylighting effects reported, but no cross-study percentage range assigned	Heterogeneous outcomes; narrative only
Cool coatings	Synnefa et al. (2007)	Surface-temperature reduction rather than institutional energy percentage	Contextual primary evidence
Window design/cross-ventilation	Ragab et al. (2025)	1–2°C temperature reduction; 36% CO ₂ reduction	Institutional comfort/IAQ outcome, not an energy-saving percentage

4.4 Geographical and Climate Factors

Climate explains part of the variation in passive-cooling performance. Warm-humid locations can benefit from air movement, but high humidity can constrain evaporative cooling and reduce the periods during which outdoor air alone provides comfort. Hot-dry climates may permit stronger evaporative cooling and can support thermal-mass or night-ventilation strategies where diurnal temperature differences are favourable. Mediterranean climates may support seasonal combinations of shading, natural ventilation and mixed-mode operation. Direct comparison of percentage savings across these contexts can therefore be misleading.

Geographic coverage is also uneven. Sub-Saharan Africa and South America are weakly represented in the evidence map. This limits transferability because construction quality, occupancy density, maintenance capacity, energy reliability and occupant control can differ materially across regions.

4.5 Synergistic Effects and Combined Strategies

Passive measures often work as systems. Shading can reduce solar gains, insulation can slow conductive heat flow, ventilation can remove accumulated heat and adaptive operation can reduce the need to maintain a narrow temperature set-point. However, synergy is not guaranteed. More insulation can retain unwanted internal heat if night-time heat removal is inadequate; large glazed areas can improve daylight while increasing solar gain; and high ventilation rates can introduce hot outdoor air during unfavourable periods. Measures should therefore be coordinated around climate, orientation, occupancy and operating schedules.

4.6 Methodological Limitations and Quality of Evidence

The evidence base is heterogeneous and includes simulations, field surveys, monitoring studies, experiments, reviews and conceptual publications. These designs provide different types of evidence and cannot be treated as directly equivalent. Simulation studies are useful for testing design alternatives but remain dependent on assumptions regarding occupancy, window operation, infiltration, internal heat gains, weather data and

material properties. Field studies provide stronger evidence of actual building operation but are often limited by short monitoring periods and specific climatic or geographic settings.

To reduce inappropriate comparison and double-counting, primary empirical studies were separated from reviews, meta-analyses and conceptual sources during the revised synthesis. Institution-specific field studies and validated simulations were used more directly in interpreting thermal-comfort and energy outcomes, while general-building studies and secondary sources were treated primarily as supporting or contextual evidence. Nevertheless, the absence of a formal study-level risk-of-bias assessment remains a methodological limitation and should be addressed in future systematic-review updates.

The search strategy also has limitations. Scopus and Web of Science were not searched, Google Scholar indexing is not fixed, and independent duplicate screening was not documented. These factors may have resulted in missed studies or introduced selection and extraction error.

4.7 Implications for Design and Policy

For new institutional buildings, the evidence supports a passive-first sequence in which orientation, openings, solar control and envelope performance are resolved before mechanical cooling capacity is finalised. Where climate permits, mixed-mode systems can provide mechanical support during periods when passive operation is insufficient. Adaptive comfort criteria may help prevent unnecessary overcooling when occupants have appropriate opportunities to adapt and indoor air quality remains acceptable.

For existing buildings, targeted measures such as external shading, roof treatments and operable-window improvements may be more practical than major reconstruction. However, the reviewed literature provides limited lifecycle-cost and maintenance evidence. Public institutions therefore still need better information on payback periods, durability and long-term performance.

5. CONCLUSION

Passive cooling can improve thermal conditions and reduce reliance on mechanical cooling in institutional buildings, but the evidence does not support a universal 9–62% energy-saving range. The revised synthesis separates primary empirical evidence from secondary reviews and restricts direct quantitative statements to outcomes traceable to original primary studies. The clearest energy result in the directly relevant institutional evidence was the 18–33% annual primary-energy saving reported for natural ventilation in Spanish school buildings by Gil-Baez et al. (2017).

Adaptive-comfort studies also indicate that naturally ventilated educational buildings can support acceptable conditions outside static-model expectations. The previously stated 1–3°C range has been narrowed to approximately 1–2°C in line with the specific evidence identified for Hwang et al. (2009). This should not be treated as a universal offset because climate, occupant adaptation and building operation remain important.

The evidence base remains limited by heterogeneous methods, sparse long-term monitoring, weak geographic representation in sub-Saharan Africa and South America, limited lifecycle-cost data and incomplete coverage of curated bibliographic databases. Future studies should monitor institutional buildings over longer periods, report comparable thermal-comfort, indoor-air-quality, energy and cost outcomes, and prioritise under-represented climates. Future systematic-review updates should include Scopus and/or Web of Science, use independent duplicate screening and extraction, apply an appropriate study-level critical-appraisal method where feasible, and prospectively register or publicly archive the review protocol.

Declarations

Conflict of Interest Statement

The authors affirm that the work described in this article was not influenced by any known competing financial interests or personal relationships.

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Data Availability Statement

The evidence used in this systematic review consists of published peer-reviewed literature. No new primary dataset was created.

Author Contributions

Author-contribution details are provided on the title page for double-blind peer review.

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