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# *Thermal Comfort and Learning Experience on Semi-Outdoor Space of Nature-Based Schools: A Scoping Review*

Dadang Hartabela[1*], Cipta Vidyana[2], Rendy Perdana Khidmat[1], Novita Hillary Christy Damanik[1], Indah Prastiwi[1]

[1]Program Studi Arsitektur, FTIK, Institut Teknologi Sumatera
[2]Program Studi Arsitektur Lanskap, FTIK, Institut Teknologi Sumatera
Jl. Terusan Ryacudu, Way Huwi, Kec. Jati Agung, Kabupaten Lampung Selatan, Lampung 35365
*Penulis Korespondensi: dadang.hartabela@ar.itera.ac.id

***Abstract:*** *Nature-based schools increasingly adopt semi-outdoor learning spaces to support experiential education, yet thermal conditions may affect children's learning and well-being. This scoping review maps current evidence on thermal comfort, children's thermal adaptation, and learning outcomes in semi-outdoor educational settings using the PRISMA-ScR framework. Total of 42 studies were included. Studies were classified into two evidence tiers: 13 core studies involving children or school environments and 29 contextual studies on outdoor thermal comfort in parks, campuses, and streets that informed transferable design principles. Core evidence suggests that children demonstrate behavioural and psychological adaptations that partially alleviate thermal discomfort, while excessive heat is generally associated with reduced concentration and academic performance. Contextual evidence identifies mean radiant temperature, shading, and vegetation as key passive cooling strategies. These findings underscore the importance of climate-responsive educational design and emphasize the need for longitudinal, child-focused research using appropriate thermal comfort indices.*

***Keywords:*** *semi-outdoor classroom; outdoor learning; elementary students; tropical climate; scoping review*

# Kenyamanan Termal dan Pengalaman Belajar di Ruang Semi-Terbuka Sekolah Berbasis Alam: Tinjauan Lingkup

**Abstrak:** Sekolah berbasis alam semakin banyak menerapkan ruang belajar semi-terbuka untuk mendukung pembelajaran berbasis pengalaman, namun kondisi termal pada lingkungan tersebut berpotensi memengaruhi proses belajar dan kesejahteraan anak. *Scoping review* ini memetakan bukti ilmiah mengenai kenyamanan termal, adaptasi termal anak, serta dampaknya terhadap hasil belajar pada lingkungan pendidikan semi-terbuka dengan mengikuti pedoman PRISMA-ScR. Sebanyak 42 studi diikutsertakan dalam kajian ini. Studi diklasifikasikan menjadi dua kelompok, yaitu 13 studi inti yang melibatkan anak atau lingkungan sekolah dan 29 studi kontekstual mengenai kenyamanan termal ruang luar pada taman, kampus, dan jalan sebagai dasar penyusunan prinsip desain yang dapat diadaptasi. Hasil kajian menunjukkan bahwa anak memiliki kemampuan adaptasi perilaku dan psikologis terhadap kondisi termal, sementara paparan panas berlebih cenderung menurunkan konsentrasi dan performa belajar. Bukti kontekstual menegaskan pentingnya suhu radiasi rata-rata, naungan, dan vegetasi sebagai strategi pendinginan pasif, sekaligus menunjukkan perlunya penelitian longitudinal dengan indeks kenyamanan termal yang dirancang khusus untuk anak.

**Kata kunci**: kelas semi-outdoor; pembelajaran outdoor; siswa sekolah dasar; iklim tropis; tinjauan lingkup

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# 1. Introduction

The global discourse on sustainable and student-centered education has progressively directed attention towards nature-based schools—educational institutions that integrate natural environments into learning as a fundamental pedagogical principle. Unlike conventional schools constrained by enclosed built environments, nature-based schools position students within or adjacent to natural settings, enabling direct engagement with outdoor and semi-outdoor spaces as primary learning venues. This model has expanded from Scandinavian forest schools to tropical-zone nature-based schools in Southeast Asia, reflecting shared recognition of the developmental and well-being benefits associated with nature-connected learning [1], [2], [3].

Among the environmental parameters influencing students' performance and well-being, thermal comfort is a critical yet frequently underappreciated determinant. The thermal environment of a learning space—shaped by air temperature, mean radiant temperature, relative humidity, and air velocity—profoundly influences physiological, psychological, and cognitive functioning [4], [5], [6]. In educational settings, sub-optimal thermal conditions have been linked to reduced concentration and diminished task performance [7], [8].

While evidence on thermal comfort in indoor classrooms is relatively well-established [9], [10], thermal environments in semi-outdoor and outdoor educational spaces remain substantively underdeveloped. Semi-outdoor spaces—open-sided pavilions, covered courtyards, shaded verandas, and roofless learning alcoves—are simultaneously shaped by outdoor meteorological dynamics and architectural interventions, creating complex thermal microclimates that demand context-specific evaluation [11], [12].

Children constitute a physiologically and behaviourally distinct population from adults: their higher surface-area-to-body-mass ratio, developing thermoregulatory systems, and greater dependence on behavioural adaptation render them more susceptible to thermal stress [13], [14], [15]. Their thermal perception may also differ from adult norms, raising questions about applying standard indices such as PMV and PET to child populations without recalibration [16], [17].

In tropical and subtropical climates, maintaining acceptable thermal conditions in semi-outdoor educational environments is compounded by persistently elevated ambient temperatures, intense solar radiation, and high humidity [18], [19]. Yet many nature-based schools in these zones continue to conduct core learning activities in semi-outdoor settings without mechanical cooling, relying on passive design and occupants' adaptive capacity. The extent to which such settings support or hinder learning remains empirically unresolved.

A preliminary search of the literature indicated that empirical work situated specifically at the intersection of nature-based schools, children, and semi-outdoor thermal comfort is sparse and methodologically heterogeneous — spanning field measurement, survey, and simulation studies across widely different climates and building types. This heterogeneity, rather than a gap to be forced into a single quantitative synthesis, is the primary justification for a scoping approach: the goal of this review is to map the extent, range, and nature of available evidence, clarify key concepts, and identify research gaps [20] rather than to estimate a pooled effect size.

This review is guided by four research questions. First, it examines the prevailing thermal comfort conditions reported in semi-outdoor educational spaces across different climatic contexts. Second, it investigates how children adapt both thermally and behaviourally to semi-outdoor learning environments, while comparing their responses with adult thermal comfort norms and established thermal comfort models. Third, it synthesizes the existing evidence on the effects of thermal conditions on children's learning experiences, cognitive performance, and classroom engagement. Finally, it explores design strategies and environmental interventions that have been shown to improve thermal comfort, drawing on evidence from both school-based studies and transferable findings from broader outdoor thermal comfort research, with particular relevance to semi-outdoor nature-based school environments.

The review contributes to interdisciplinary knowledge at the nexus of environmental science, educational architecture, and climate-responsive design, while being explicit about where conclusions rest on direct child/school evidence versus transferable evidence from general outdoor thermal comfort research.

## 2. Methodology

### 2.1. Review Design and Justification

This review adopts a scoping review design, following the methodological framework of Arksey and O'Malley [20] as refined by Levac [20], and reported in accordance with the PRISMA extension for Scoping Reviews (PRISMA-ScR) [21]. A scoping approach was chosen over a systematic review with meta-analysis for three reasons. First, literature specifically addressing thermal comfort in nature-based-school, child-occupied semi-outdoor spaces is limited, so the review draws additionally on a broader, contextually related body of outdoor thermal comfort research to characterize general environmental principles. Second, included studies vary widely in population (children vs. adults), design (field measurement, survey, CFD simulation, review), climate, and reported metrics, making quantitative pooling inappropriate. Third, the aim of the review is to map the breadth and nature of available evidence and to identify gaps — the defining purpose of a scoping review — rather than to test a specific hypothesis about effect size.

### 2.2. Search Strategy

A literature search was conducted in Scopus, Web of Science, ScienceDirect, and SpringerLink for publications from 2000–2025, combining three concept blocks: (1) thermal comfort terms ("thermal comfort", "PET", "PMV", "UTCI", "mean radiant temperature", "heat stress"); (2) educational-context terms ("school", "classroom", "nature-based school", "forest school", "learning space"); and (3) outdoor-environment terms ("semi-outdoor", "outdoor", "naturally ventilated", "passive cooling"). Reference lists of retrieved articles were manually reviewed for additional relevant studies (snowballing).

## 2.3. Selection and Evidence Tiering

Because directly relevant child/school studies were expected to be scarce, records were not excluded solely for lacking a child population; instead, every included record was explicitly classified into one of two evidence tiers, reported transparently in Table 1, so that readers can weigh each finding by the directness of its evidential support:

1. Core evidence: studies whose subjects, setting, or explicit focus involve children and/or K-12 educational environments (n = 13).
2. Contextual evidence: studies on general outdoor thermal comfort (urban parks, streets, university campuses, façades) that do not involve child populations or school settings, but whose environmental-physics and design findings are potentially transferable to semi-outdoor school design (n = 29).

Records were retained if they reported empirical or review-level evidence on outdoor/semi-outdoor thermal comfort, thermal perception, or the thermal environment–learning relationship, published 2000–2025 in a peer-reviewed venue with retrievable full text. Duplicate records referring to the same publication (identified by matching DOI) were merged into a single entry; one such duplication was identified and corrected during data verification (see Section 3.1).

## 2.4. Screening Process

Titles and abstracts of retrieved records were screened independently by two reviewers against the criteria above; full texts of potentially relevant records were then read in full. Disagreements were resolved by discussion. A simplified PRISMA-ScR flow diagram (identification → screening → eligibility → inclusion) documents the selection process.

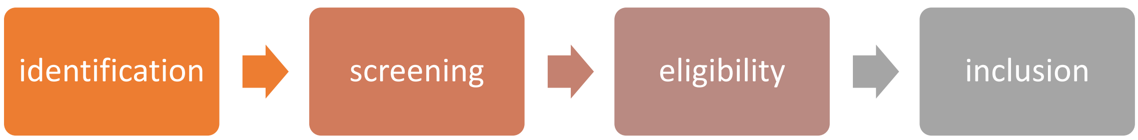


**Fig 1**. Flow Diagram for Scoping Review

## 2.5. Data Charting

A charting form was piloted on five studies and then applied to the full sample, extracting: author(s)/year, country, climate classification, evidence tier, study setting, methods, thermal comfort indices used, key findings (recorded as stated by the original authors, verified against the source abstract/DOI), and design implications. No study was excluded on methodological-quality grounds; because this is a scoping review, formal quality/risk-of-bias appraisal was not performed, consistent with PRISMA-ScR guidance that such appraisal is optional for scoping reviews [21].

### 2.6. Synthesis Approach

Findings are synthesized narratively, organized by the four research questions, following the thematic synthesis logic of Thomas and Harden [22]: line-by-line coding of extracted findings, development of descriptive themes, and generation of analytical themes. Quantitative figures (e.g., a reported PET range or a temperature–performance association) are reported only when directly attributable to a specific, named study, and are not pooled or averaged across studies, consistent with the decision not to conduct a meta-analysis.

## 3. Results and Discussion

### 3.1. Overview of Included Studies

The scoping search identified 42 unique studies published between 2003 and 2025 after removing one duplicate record (two entries referring to the same 2018 publication by Taleghani [23], [24] were identified during verification and merged; the corrected entry is reported under its correct scope — university campus outdoor albedo — rather than the originally miscategorized "school outdoor space / tree shading" description). Of the 42 studies, 13 are classified as core evidence (directly involving children and/or school settings) and 29 as contextual evidence (general outdoor thermal comfort research). This distribution — roughly one core study for every two contextual studies — is itself a substantive finding: it indicates that direct empirical evidence on children's thermal comfort in nature-based semi-outdoor school settings remains a comparatively small and specialized literature, embedded within a much larger body of general outdoor thermal comfort research.

Geographically, core studies are concentrated in Australia, Taiwan, Hong Kong, Costa Rica, Denmark, Argentina, and Iran, while contextual studies span a wider set of countries in East and Southeast Asia, the Middle East, Europe, and North America. Table 1 summarizes all 42 included studies with their assigned evidence tier.

**Table 1**. Summary of included studies, classified by evidence tier

| No | Author(s), Year | Tier | Country / Climate | Setting | Methods | Indices | Key Finding |
|---|---|---|---|---|---|---|---|
| 1 | Spagnolo & de Dear (2003) [12] | Core | Australia / Subtropical | Outdoor & semi-outdoor school spaces | Field meas. + survey | SET*, PET, PMV | Outdoor neutral temperature is higher than indoors, with a wider comfort range. |
| 2 | Nikolopoulou & Steemers (2003) [25] | Core | UK / Greece / Temperate / Mediterranean | Urban open spaces; schools | Field study + survey | TSV, PMV | Psychological adaptation strongly influences outdoor thermal perception. |
| 3 | Lin (2009) [26] | Core | Taiwan / Subtropical | Outdoor recreational & educational spaces | Field meas. + interview | PET | Taiwanese users show a higher neutral PET (26–30°C) than Europeans. |
| 4 | Cheung & Jim (2018) [27] | Core | Hong Kong / Subtropical | School courtyards & outdoor play areas | Microclimatic meas. + walkthrough | PET, UTCI | Tree canopy and vertical greening reduce PET and improve comfort. |
| 5 | Porras-Salazar et al. (2018) [28] | Core | Costa Rica / Tropical | Naturally ventilated elementary classrooms | Field intervention (AC) + survey | Ta, thermal sensation | Cooling classrooms by ~5°C shifted sensation from hot to neutral and improved task performance. |

| No | Author(s), Year | Tier | Country / Climate | Setting | Methods | Indices | Key Finding |
|---|---|---|---|---|---|---|---|
| **6** | Taleghani (2018) [28] | Contextual | Netherlands / Temperate oceanic | University campus (outdoor) | Field meas. + modelling | PET | Increasing surface albedo on campus pavements reduces outdoor summer heat stress. |
| **7** | Haverinen-Shaughnessy & Shaughnessy (2015) [29] | Core | USA / Temperate | Elementary school classrooms | Cross-sectional field study | Temperature, WBGT | Higher classroom temperatures are associated with lower standardized test scores. |
| **8** | Ruiz & Correa (2015) [30] | Core | Argentina / Warm semi-arid | School outdoor spaces | Field meas. + CFD | PET, PMV, MRT | Vegetation lowers air temperature and MRT, improving courtyard comfort. |
| **9** | Kuo, Barnes & Jordan (2019) [1] | Core | USA / Varied | Nature-based learning environments | Narrative review | N/A | Nature exposure improves attention, reduces stress, and enhances learning. |
| **10** | Johansson et al. (2014) [31] | Core | Multiple (review) / Varied | Semi-outdoor / outdoor comfort studies | Methodological review | PET, UTCI, various | Highlights the need for standardized instruments/methods in outdoor comfort studies. |
| **11** | Zomorodian et al. (2016) [17] | Core | Iran (review) / Varied | Educational buildings (review) | Literature review | PET, PMV, UTCI | Thermal comfort thresholds in schools vary with climate, age, and acclimatization. |
| **12** | Toftum et al. (2015) [16] | Core | Denmark / Cool temperate | Naturally ventilated school classrooms | Cross-sectional field study | Ventilation mode, CO2 | Mechanically ventilated classrooms are associated with higher academic achievement than naturally ventilated. |
| **13** | Wargocki & Wyon (2007) [16] | Core | Multiple / Varied | Indoor / partially naturally ventilated classrooms | Experimental field studies | Temperature, CO2, PMV | Higher classroom temperatures reduce the speed and accuracy of schoolwork. |
| **14** | de Dear et al. (2015) [32] | Core | Australia / Subtropical | Outdoor & semi-outdoor school spaces | Field study + survey | PET, SET* | Psychological adaptation shifts children's outdoor neutral temperature. |
| **15** | Fong et al. (2019) [33] | Contextual | Southeast Asia (review) / Tropical | Outdoor thermal comfort (general) | Critical appraisal / review | N/A | Calls for more research on adaptation, ethnicity, and health in tropical outdoor comfort. |
| **16** | Chan & Chau (2021) [34] | Contextual | Hong Kong / Subtropical | Urban parks | Field meas. + modelling | PET, UTCI | Tree cover and building configuration strongly shape seasonal park thermal comfort. |
| **17** | Klemm et al. (2015) [35] | Contextual | Netherlands / Temperate | Urban green spaces | Field meas. + survey | PET | Green infrastructure improves both perceived and measured outdoor thermal comfort. |
| **18** | Rupp et al. (2015) [36] | Contextual | N/A (review) / N/A | Built environment (general) | Literature review | N/A | Thermal comfort assessment must be tailored to indoor, semi-outdoor, or outdoor context. |
| **19** | Hanan et al. (2020) [37] | Contextual | Japan / Subtropical | Science/research park | Field meas. + survey | PET | Air temperature and clothing insulation strongly shape outdoor thermal comfort. |
| **20** | Li et al. (2020) [38] | Contextual | Hong Kong / Subtropical | Outdoor public space | Field meas. | UTCI | Sun and wind exposure jointly determine outdoor thermal sensation. |

| No | Author(s), Year | Tier | Country / Climate | Setting | Methods | Indices | Key Finding |
|---|---|---|---|---|---|---|---|
| **21** | Yuan et al. (2022) [39] | Contextual | Japan / Subtropical | Building façade / outdoor area | CFD + model experiment | Ta, WBGT, SET* | Retro-reflective façades reduce outdoor heat-stress indices. |
| **22** | Tuohy et al. (2010) [40] | Contextual | UK / Temperate | Office buildings (review) | Literature review | Adaptive comfort model | Adaptive comfort strategies reduce building cooling energy demand. |
| **23** | Ma et al. (2019) [41] | Contextual | China / Subtropical | Commercial pedestrian street | Field meas. + survey | PET, TSV | Pedestrians' acceptable PET ranges from 20.6–27.5°C. |
| **24** | Cheng et al. (2020) [42] | Contextual | China / Subtropical | Urban park | Field meas. + survey | PET | Water bodies, shading, and surface material strongly affect park thermal comfort. |
| **25** | Taleghani et al. (2015) [23] | Contextual | Netherlands / Temperate | Pedestrian urban forms | Field meas. + modelling | PET | Urban form affects thermal comfort mainly through solar exposure and MRT. |
| **26** | Mirabi & Nasrollahi (2020) [43] | Contextual | N/A (review) / N/A | Urban façade geometry | Literature review | N/A | Façade geometry shapes airflow, comfort, and building energy performance. |
| **27** | Lin et al. (2008) [44] | Contextual | N/A / N/A | Vegetation patterns (simulation) | Numerical simulation | SET | Trees generally improve thermal comfort despite reducing wind speed. |
| **28** | Barakat et al. (2017) [45] | Contextual | Egypt / Hot arid | Urban open space | Numerical simulation | Air temp., PMV | Street layout and material choice shape outdoor thermal comfort in hot-arid cities. |
| **29** | Sayad et al. (2021) [46] | Contextual | Algeria / Hot arid | Urban open space | Field meas. + survey | Comfort thresholds | Vegetation species and layout shape outdoor comfort in hot climates. |
| **30** | Elnabawi et al. (2016) [47] | Contextual | Egypt / Hot arid | Urban open space | Field meas. | Thermal perception | Documents outdoor thermal perception patterns in hot-arid Cairo. |
| **31** | Alfian et al. (2017) [48] | Contextual | Indonesia / Tropical | Urban street | Field meas. + simulation | THI | Layered vegetation (trees, shrubs, ground cover) improves streetscape comfort. |
| **32** | Mendes et al. (2025) [49] | Contextual | Portugal / Warm-summer Mediterranean | University campus | Field measurement | PET, mPET | Microclimate-sensitive landscape design enhances outdoor comfort on campus. |
| **33** | Aram et al. (2020) [50] | Contextual | Spain / Subtropical | Urban park | Field meas. + survey | PET, PTC, CEI | Large urban parks provide measurable physiological and psychological cooling benefits. |
| **34** | Lau & Choi (2021) [51] | Contextual | Hong Kong / Subtropical | Urban open space | Survey | TSV, TCV | Perceived environmental quality improves thermal comfort and tolerance. |
| **35** | Damayanti et al. (2020) [52] | Contextual | Indonesia / Tropical | Semi-outdoor university canteen | Field meas. + survey | Thermal comfort index | Passive design and ventilation improve comfort in semi-outdoor campus spaces. |
| **36** | Zhang et al. (2021) [53] | Contextual | China / Cold region | University campus (outdoor) | Field meas. + survey | PET, TSV, PANAS | Thermal perception and emotional state jointly shape outdoor comfort. |
| **37** | Lam et al. (2018) [54] | Contextual | Australia / Temperate oceanic | Botanic gardens | Field meas. + survey | UTCI | Heatwaves alter thermal perception and adaptive clothing behaviour. |

| No | Author(s), Year | Tier | Country / Climate | Setting | Methods | Indices | Key Finding |
|---|---|---|---|---|---|---|---|
| **38** | Li, W. et al. (2025) [55] | Contextual | China / Subtropical | Urban green space (campus) | Field meas. | THI | Dense, diverse vegetation improves microclimate and thermal comfort. |
| **39** | Thorsson et al. (2004) [56] | Contextual | Sweden / Temperate oceanic | Urban park | Field meas. + survey | PMV | Users adapt behaviourally (seating, clothing, location) to outdoor thermal. |
| **40** | Makaremi et al. (2012) [57] | Contextual | Malaysia / Tropical | University campus (outdoor) | Field meas. + survey | PET | Shaded outdoor campus spaces support tropical thermal adaptation. |
| **41** | Fang et al. (2017) [58] | Contextual | China / Subtropical | Urban open space | Field meas. + survey | PMV, TSV | Adaptive thermal models predict outdoor sensation better than PMV alone. |
| **42** | Lin, T.P. et al. (2010) [59] | Contextual | Taiwan / Subtropical | University campus (outdoor) | Field meas. + survey | PET, SVF | Balanced seasonal shading (sky-view factor + vegetation) improves year-round comfort. |

**(Core = direct child/school evidence; Contextual = general outdoor thermal comfort evidence)**

## 3.2. Thermal Comfort Conditions in Semi-Outdoor Educational Spaces

Core studies conducted in school settings report that semi-outdoor spaces in subtropical and tropical climates typically register neutral or acceptable temperatures above those found indoors, with wider comfort bands than standard indoor models predict [12], [32]. Field evidence from an elementary school intervention in Costa Rica showed that lowering classroom temperature by approximately 5°C (from about 30°C to 25°C) shifted children's thermal sensation from 'hot' toward 'neutral' and improved schoolwork performance [28], one of the few studies in this review offering a directly attributable, quantified child-specific effect.

Contextual studies, though not involving children, consistently identify mean radiant temperature (MRT) as a dominant driver of outdoor heat stress, frequently outweighing air temperature [28], [39], [60]. Because these findings derive from adult populations in parks, streets, and campuses, they should be read as indicating plausible physical mechanisms transferable to semi-outdoor school design, not as direct evidence of children's experience.

## 3.3. Thermal Adaptation of Children in Outdoor Educational Settings

Among core studies, children demonstrate physiological, behavioral, and psychological adaptation to elevated thermal conditions. Psychological adaptation (expectation, perceived control, and environmental familiarity) moderates thermal perception in both adult and child populations [25], and children's engagement and curiosity in nature-connected learning may similarly buffer discomfort, consistent with the broader restorative-environments and biophilic-design literature. Zomorodian [17] note that comfort thresholds in educational buildings vary with climate, age, and acclimatization, cautioning against applying a single universal standard to all school-age populations. However, the number of core studies reporting quantified child-specific adaptation limits (e.g., heat-exhaustion or dehydration thresholds) within this sample is small, and this is flagged as a priority evidence gap rather than assumed from the adult-focused contextual literature.

### 3.4. Influence of Microclimatic Variables on Thermal Comfort

Across contextual studies, shading and vegetation consistently reduce MRT and improve perceived comfort [17], [35], [44] and wind/ventilation improves convective cooling [19], [39] Surface albedo and material choice also measurably affect outdoor heat load [45], [61] These mechanisms are physically general and plausibly transferable to semi-outdoor school design; however, because none of the studies reporting them were conducted with children as subjects, the magnitude of benefit specifically for school-age users in nature-based schools has not been directly measured and should be treated as a hypothesis for future school-based field studies rather than an established finding.

### 3.5. Thermal Conditions on Learning Experience

The strongest direct evidence linking thermal conditions to learning outcomes comes from indoor/naturally-ventilated classroom studies rather than semi-outdoor settings specifically. Wargocki and Wyon [8] report that classroom temperatures above approximately 23°C are associated with reduced speed and accuracy of schoolwork. Haverinen-Shaughnessy [29] similarly report an inverse association between classroom temperature and standardized test performance among elementary students. Toftum [16] found that Danish schools with mechanical ventilation had higher academic achievement indicators than those with natural ventilation only. These three core studies converge on the same direction of effect (higher heat → lower performance), which is the most defensible generalizable claim this review can support; the exact magnitude reported in each study is specific to its own national testing system and should not be pooled across studies with different outcome measures.

Direct evidence on semi-outdoor (as opposed to indoor) classrooms and learning performance is markedly thinner within the core-evidence set. This is identified as the single most important evidence gap raised by this review, and is discussed further in Section 3.6.

### 3.6. Design Strategies and Research Gaps

Combining core and contextual evidence, five design strategies recur across the literature: shading systems, natural ventilation optimization, vegetation/green infrastructure, high-albedo or reflective materials, and site-specific spatial configuration. Each has direct or transferable evidential support (see Table 1); none has been evaluated through a controlled pre/post field study specifically in a semi-outdoor nature-based school with children as participants. This review therefore recommends these strategies as evidence-informed hypotheses for design, rather than as fully validated child-specific interventions.

Priority gaps for future research are: (1) longitudinal, multi-season studies of children's thermal adaptation specifically in semi-outdoor nature-based school settings; (2) child-specific thermal comfort indices, given that PMV/PET were calibrated on adult populations; (3) controlled or quasi-experimental evaluation of shading, ventilation, and vegetation interventions with learning-outcome measures in real school settings; and (4) broader climatic coverage, since core evidence is currently concentrated in a small number of countries.

## 4. Conclusions

This scoping review maps 42 studies relevant to thermal comfort and learning experience in semi-outdoor educational spaces, of which 13 directly involve children or school settings (core evidence) and 29 provide transferable evidence from general outdoor thermal comfort research (contextual evidence). Distinguishing these tiers is itself a key contribution: it shows that while the physical mechanisms of outdoor heat stress and passive cooling are well documented in the wider literature, direct evidence of how children specifically experience and adapt to semi-outdoor school thermal environments — and how this affects their learning — remains limited to a small set of studies concentrated in a few countries.

Within that limited core evidence, findings converge on three points: semi-outdoor educational spaces can exceed indoor comfort thresholds, particularly in tropical and subtropical climates; children show meaningful behavioral and psychological adaptation but with likely physiological limits that remain under-quantified; and elevated thermal load is associated with reduced concentration and academic performance, primarily documented so far in indoor/naturally-ventilated classrooms rather than semi-outdoor spaces per se. Design strategies such as shading, vegetation, ventilation, and reflective materials are well supported by contextual (adult, general-outdoor) evidence and represent reasonable, evidence-informed starting points for nature-based school design, pending direct validation with child populations. Longitudinal, child-specific, and intervention-based research in semi-outdoor nature-based school settings is the clearest priority to close the gap identified by this review.

## 5. Ethical Considerations

The authors declare that generative artificial intelligence tools were used to assist with language editing, structural organization, and preliminary literature screening during the preparation of this manuscript. All AI-assisted outputs, including the classification of studies into evidence tiers and the verification of bibliographic details against original sources, were critically reviewed and corrected by the authors, who retain full responsibility for the accuracy, integrity, and originality of the content presented. During revision, one duplicate study entry and two inaccurate bibliographic records identified in an earlier draft were corrected against their original sources.

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