

Review Article

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Climate-Responsive Façade Strategies for School Buildings in India's Composite and Transitional Climates: A Systematic Review

Kalyani Nilesh Junankar¹, Tarika Mohite Dagadkar², Gauri Shiurkar¹, Vikas gulia³

¹Assistant Professor, Symbiosis School of Architecture, Urban Development, Planning and Design (SSAUD), Symbiosis Skills and Professional University (SSPU), Pune, India

²Smt Manoramabai Munde College of Architecture, Nagpur

³Symbiosis International (Deemed University), Symbiosis Institute of technology, Pune
Corresponding author: vikas.gulia@sitpune.edu.in

ABSTRACT: School facades control solar gain, daylighting, ventilation and noise in crowded classrooms. Most Indian classrooms are naturally ventilated, yet school façade guidance is generic and rarely considers embodied impacts. This review examines 2015–2026 evidence on climate-responsive school facades relevant to India's composite and transitional climates and identifies gaps limiting their implementation in Pune. This PRISMA 2020 systematic review used fourteen search strings in Consensus, an AI-assisted academic search engine indexing Semantic Scholar, Scopus, PubMed and arXiv, along with a preliminary bibliography. Of 336 records, 314 were screened after de-duplication and 94 studies were included. The evidence is voluminous but poorly aligned with the problem: 44 studies concern educational buildings, 33 concern India, and only 12 concern both; none combines façade design with life-cycle assessment (LCA). Simulation dominates (46%), and no Indian school façade study is field-validated. Fixed shading and window-to-wall ratio (WWR) optimisation reduced energy or cooling demand by 2–36% compared with study baselines, but the optimal WWR ranged from 10% to 60% and was not transferable between sites. Students in naturally ventilated Indian classrooms accepted operative temperatures of 15–34 °C, much wider than the National Building Code range of 21–26 °C, indicating that code-based façade optimisation overestimates cooling requirements. LCA studies show that reducing operational energy may increase whole-life carbon, depending on grid carbon intensity; this trade-off is untested in Indian schools. The review proposes a four-stage approach for school facades in Pune and similar climates, encompassing façade variables, daylight and adaptive-comfort metrics, whole-life carbon and multi-criteria decision-making.

Graphical Abstract



1. INTRODUCTION

1.1 Background

The façade is the main interaction between the inside and outside climate of the building. It is now known that it could be treated as an enclosure, aesthetic surface, and at the same time a system of performance that controls the solar heat gain, daylight admission, glare, natural ventilation, acoustic insulation and the impact of the materials used (Cucuzzella et al., 2023, Tahmasbi et al., 2025). Façade decisions are made at a very early stage in the design process, and are costly to change and make a significant proportion of the operational and embodied carbon (Echenagucia et al., 2022; Prideaux et al., 2024).

The case of school is a tough one. Children are more heat-sensitive than adults, view and thermal conditions, as well as air quality, have a significant impact on their learning in classrooms occupied at a high density, mostly during the daytime and in the hottest part of the year (Baloch et al., 2020, Honan et al., 2024, Manfren et al., 2026). In India, most of the school classrooms are naturally ventilated and utilize windows, fans, and adaptation of occupants to the environment without mechanical cooling (Kapoor et al., 2021a, Jindal, 2018). The façade in this case bears the majority of the burden of controlling the environment. However, (Kapoor et al., 2021a) found that the body of knowledge related to IEQ around Indian classrooms is fragmented and there is no standardized approach available to measure classroom environment.

Climate change worsens the issue. Here, warming trends have been observed at Indian climate stations (Saifudeen et al., 2023) observed an increase of approximately 60% in heat-stress hours in New Delhi between 1991 and 2019 (Debnath et al., 2026), and climate model-derived projections of overheating classrooms for the future indicate similarly high school-stock increases in other parts of the world by 2050 (Manfren et al., 2026). A façade that was designed for the current average meteorological year may perform less than optimally during its design period.

1.2 The composite transitional climate problem and the case of Pune

The building codes adopted for India have five climate zones. Hot-dry, warm-humid, composite, temperate and cold (Bureau of Indian Standards [BIS], 2016). The extent of natural comfort potential and passive cooling potential ranges from 23% to 46% of year in the composite zone with the highest value in the largest city, and from 26.5% to 53.5% in the same zone, respectively, across 21 composite-zone cities (Kishore et al., 2018). It is found that the five-zone classification is sub-optimal for separating the locations, and six or more zones are even better for representing the thermal response of buildings (data-driven reclassifications, silhouette index - 0.2, versus 0.21 for an alternative classification based on cluster).

The Pune city (18.52° N, 73.86° E; c. 560 m above mean sea level) does not belong to any of the above-mentioned zones. Based on the ECBC climate zoning (BEE, n.d.), buildings in Pune are considered warm and humid. According to the city-level strategy matrices, Pune is a temperate zone (Thakur et al., 2021) and in Köppen-Geiger system it is tropical wet-and-dry,

bordering on hot semi-arid (Beck et al., 2018). The National Building Code only designates a zone when all conditions in the code hold true for six months or longer, otherwise a location is considered composite (BIS, 2016). The cities of the plateau are situated at the interface between the categories as they have a hot, dry premonsoon, a humid monsoon and a mild winter. Data-driven reclassifications verify that the five-zone scheme is not a good fit for such sites (Gupta et al., 2024; Jain et al., 2022). This review thus considers Pune to be a transitional climate. It has the same design challenges as the composite zone, namely hot pre-monsoon months, humid monsoon, and mild winter, and evidence is not selected from a fixed pre-designed category, but rather from multiple categories.

1.3 Aim, research questions and contribution

The goal is to systematically and transparently understand what is known about climate-responsive façade strategies for school buildings that are relevant to composite and transitional climates of India, and what needs to be understood before these strategies can be optimised for school buildings in Pune.

This review is based on four research questions (RQs):

RQ1: What façade strategies have been assessed for educational buildings and what performance changes are reported?

RQ2: What are the suitable comfort criteria and performance metrics for naturally ventilated Indian classrooms?

RQ3: How do the current studies incorporate the life-cycle (embodied and operational) impacts and façade performance?

RQ4: What are the gaps that hinder evidence-based façade optimisation for schools in Pune and like climates?

The review brings three contributions: (i) a PRISMA-documented data base of 94 studies, with explicit evidence mapping; (ii) synthesis of the data based on critical analysis that differentiates between robust evidence and context-specific or contested evidence and (iii) an integrated performance-life-cycle framework and research agenda for school façades in composite-transitional climates.

2. CONCEPTUAL BACKGROUND

2.1 Façade design variables and performance outcomes

Performance of a sustainable building can be presented as a relationship between variables that can be controlled by the designer, and the outcomes that can be achieved as illustrated in Table 1. There are a number of variables that can be controlled for school facades such as orientation, WWR per façade, type of shading, shading geometry, properties of the glazing, wall assembly and surface finish, and vegetation, outcomes of interest are energy and carbon, indoor environmental quality and learning-relevant conditions, and cost and durability. This section covers solar geometry at Pune and its implications on façade.

Table 1. Façade design variables and performance outcomes considered in this review (Lakhdari et al., 2021; Chaturvedi et al., 2024a)

Design variables (independent)	Performance outcomes (dependent)	Typical metrics
Orientation and building form	Operational energy	Energy use intensity (EUI, kWh/m ² ·yr); cooling load
Window-to-wall ratio (WWR) per façade, sill and head height	Daylight and visual comfort	Spatial daylight autonomy (sDA _{300/50%}), annual sunlight exposure (ASE _{1000,250}), useful daylight illuminance (UDI), daylight glare probability (DGP)
Shading- overhangs, fins, egg-crate, louvres, perforated screens (jaali)	Thermal comfort	Adaptive comfort hours (IMAC / ASHRAE 55 adaptive), overheating hours
Glazing- U-value, solar heat gain coefficient (SHGC), visible light transmittance (VLT)	Indoor air quality and ventilation	CO ₂ concentration, air-change rate, effective opening area

Design variables (independent)	Performance outcomes (dependent)	Typical metrics
Wall assembly, finish and reflectance; green façades	Whole-life environmental impact	Global warming potential (kgCO ₂ e/m ²) by EN 15978 module (A1-A3, B4, B6, C)
Adaptive or kinetic elements; building-integrated PV	Economic performance and durability	Life-cycle cost, maintenance interval, service life

2.2 Solar geometry at Pune and its façade implications

Pune is located south of the Tropic of Cancer which is why the summer sun is to the north of the zenith. At 18.52° N, as visible in figure 1, the sun's noon altitude is approximately 85° on 21 June (the sun to the north) and approximately 71° at the equinoxes and approximately 48° on 21 December (when the sun is to the south). There are three consequences for school façades. First, a simple south façade to protect is a horizontal overhang at a ratio of about 0.33 blocks at equinox noon, allowing for some low winter sun. Second, the north façade is exposed to direct early morning and late afternoon sunshine from April to August and should not be taken for granted as being “sun-free” and therefore require small vertical fins. Third, if east and west façade surfaces are to be lit by the low angle sun during the school day (08:00-15:00), the vertical devices cannot prevent this sun from reaching the surface, horizontal devices are necessary. Such relationships may be considered as being of a standard solar geometry, but are not often explicitly articulated for Indian school sites and conflict with design heuristics from other latitudes or from the southern hemisphere.

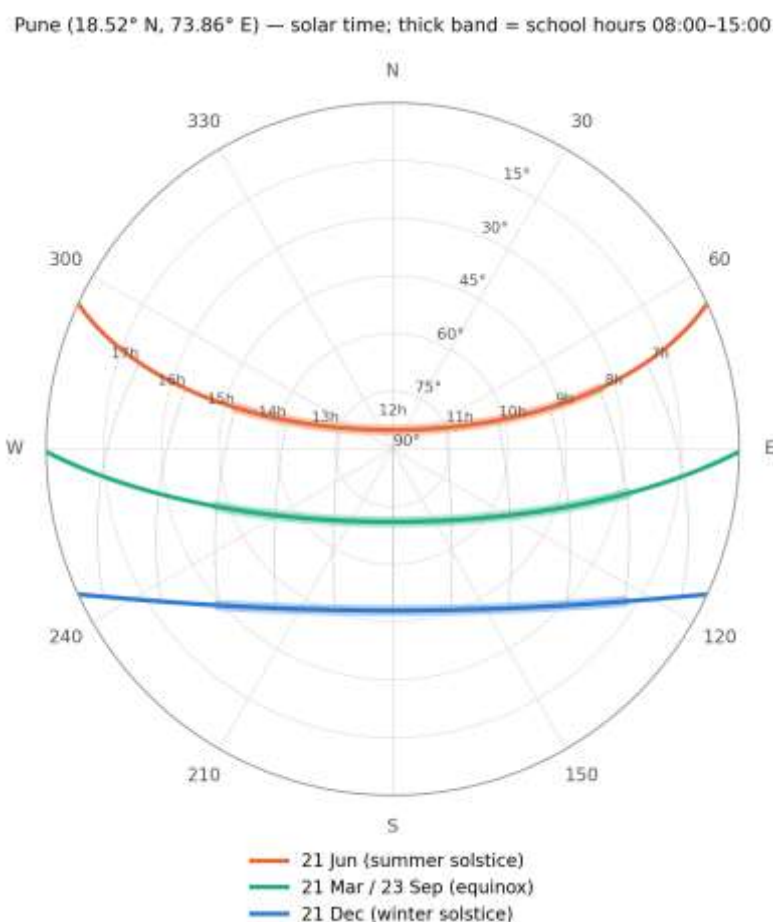


Figure 1. Sun-path diagram for Pune (18.52° N) for the summer solstice, equinoxes and winter solstice, in solar time. Thick bands represent typical school hours (08:00 to 15:00), dotted lines are hour lines. The angle is measured from the zenith along the radius of a circle (zenith/centre is 90°).

3. METHODOLOGY

3.1 Review design

This systematic review is conducted on the basis of the PRISMA 2020 guideline (Page et al., 2021) and a narrative synthesis is used due to the varying metrics and baselines used across the studies. The literature search was conducted using Consensus, an AI-powered academic search tool that is powered by Semantic Scholar, an AI search engine that indexes approximately 200 million records from Semantic Scholar, Scopus, PubMed and arXiv (Consensus NLP, Inc., 2026). Fourteen search strings were used, with a combination of façade, school, climate, comfort, daylight and life-cycle terms. The complete strings are provided in Table 2. 297 of the most relevant records per string ($n = 20$) were retrieved and 57 from a preliminary bibliography were added to the total. 314 records were screened after de-duplication and 94 studies were included following studies that were screened against eligibility criteria (Table 2).

Table 2. Search strings used (Consensus AI)

	Search string	RQ
S1	façade design optimization school classrooms daylight thermal comfort energy	RQ1
S2	thermal comfort in naturally ventilated school classrooms India composite climate	RQ2
S3	window-to-wall ratio and shading device optimization energy daylight hot climate India	RQ1
S4	life cycle assessment of building façade systems embodied carbon comparison	RQ3
S5	adaptive kinetic dynamic façades review energy daylight performance	RQ1
S6	Pune school building climate responsive design simulation daylight thermal	RQ1, RQ4
S7	climate zone classification India buildings composite climate reclassification	RQ4
S8	Jaali perforated screen façade thermal daylight performance India	RQ1
S9	green façade vertical greenery cooling effect building envelope hot climate	RQ1
S10	indoor environmental quality Indian school classrooms review CO ₂ ventilation daylight	RQ2
S11	classroom daylight and window view effect on student learning performance and wellbeing	RQ2
S12	integrating life cycle assessment early design stage building design process review architects	RQ3
S13	Pune India building energy thermal comfort climate zone study	RQ2, RQ4
S14	school buildings overheating risk future climate change passive façade adaptation	RQ4

3.2 Selection process

Following the removal of the duplicates, 314 records were screened by title and abstract and 116 items were subsequently evaluated in detail against the eligibility criteria. Ninety four studies were eligible and included in the review. Figure 2 outlines the process used to select the three projects.

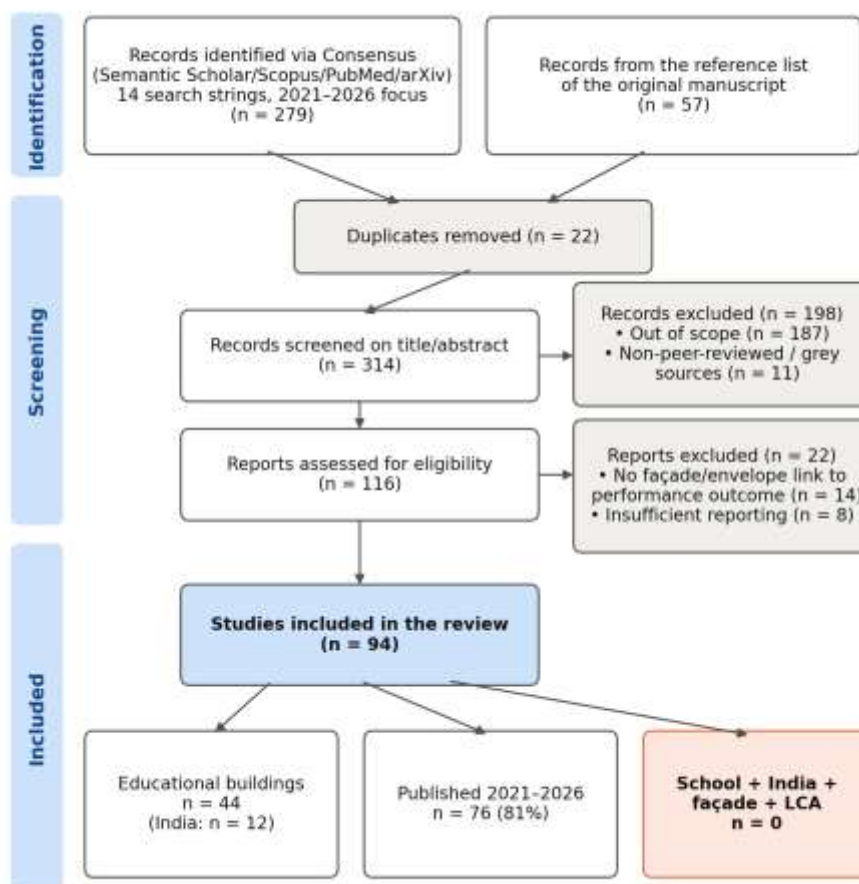


Figure 2. PRISMA 2020 flow diagram of study identification

The studies included were coded by primary theme (ten themes; Appendix A), building type (educational or other), building location (India or other), and study method (simulation, field study, review, experiment or mixed methods).

4. RESULTS

4.1 Characteristics of the evidence base

The vast majority of the included studies were published between 2021 and 2026 ($n = 76$, 81%, Figure 3). Forty-four papers are about education buildings and 33 about India, but only 12 concern educational buildings in India. Out of these 12, seven are thermal-comfort field surveys, three are about daylight in classrooms (Jayaram et al., 2025, Poptani & Parveen, 2022, Saxena et al., 2023), one is an IEQ review (Kapoor et al., 2021a) and other monitors climate-responsive institutional buildings (Manu et al., 2019). None of these papers addresses façade optimisation with respect to energy, comfort and daylight jointly, and no one considers LCA.

The most common method is simulation (43 studies, 46%) followed by reviews (26, 28%), field measurement or surveys (18, 19%), mixed methods (6) and laboratory experiments (1). The evidence for Indian schools is only in terms of occupant comfort, while all Indian school studies of façades are simulation based. Figure 4 shows the evidence map for where knowledge is concentrated, envelope and fenestration optimization is well studied for schools outside India (14 studies) and for other building types in India (6), and LCA is well studied for non-school buildings outside India (9), but the cells that matter most for the research problem, façade optimization, perforated screens, green façades, adaptive façades and LCA for Indian schools are empty.

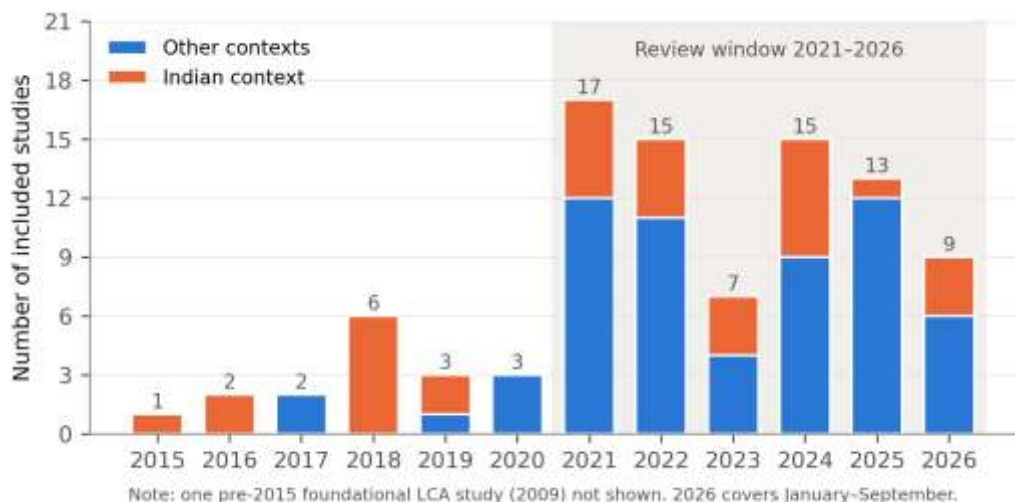


Figure 3. Year of publication of the 94 included studies, by Indian and others.

	School - India	School - other	Other building - India	Other building - other
Envelope & fenestration optimisation	-	14	6	-
Thermal comfort & adaptive models	7	-	4	-
Daylight, view & learning	3	5	1	1
IAQ & ventilation	1	2	-	-
Perforated screens (jaali)	-	-	3	1
Green façades	-	1	-	4
Adaptive / kinetic façades	-	2	-	6
LCA & embodied carbon	-	2	-	9
Climate zoning & climate-change resilience	1	5	6	1
Façade evolution, materials & durability	-	1	1	7

Figure 4. Evidence map: number of studies included per theme and context Each study is counted once, under the main theme. Empty cells (–) means no included study.

4.2 Thematic synthesis

4.2.1 Orientation, window-to-wall ratio and fixed shading

This is the most developed theme. Multi-objective optimization of classroom envelope is usually carried out using Rhino/Grasshopper and Ladybug-Honeybee (Energy Plus and Radiance) coupled with a genetic algorithm. Such optimization always provides solutions that improve the classroom performance in terms of comfort and daylighting, while reducing the energy consumption. Such optimization can lead to a reduction of energy use intensity (EUI) of 13.5-25.2% with fixed external shading in five Iranian climates (Talaei et al., 2024), 4.5-18.8% with composite shading and perforated panels in Nanchang (Wang et al., 2022), 24-28% reduction in heating and lighting energy in cold-climate Chinese schools (Zhang et al., 2017), 20% reduction using 100% sDA in an Indonesian classroom (Hakim et al., 2021) and 18.6-35.6% in rural Moroccan schools (Es-sakali et al., 2025) (Figure 5). In non- Indian school buildings, façade optimisation with respect to glazing and shading decreased EUI by 1.9-19.2% in Delhi, Ahmedabad, Mumbai and Bangalore, horizontal louvre depth, WWR and window height were identified as the most influential variables (Chaturvedi et al., 2024a), 45° louvers reduced cooling energy by 7.5-16.8% on west façades in a semi-arid city, whereas deepening an overhang to 1 m changed indoor air temperature very little (Gajjar et al., 2024).

Two cautions are in order. First, the improvements are measured against different baselines, code-reference buildings, unshaded cases, “average” designs or worst cases, so magnitudes are not comparable. (Chaturvedi et al. 2024b) report a 72% reduction in cooling demand for Jaipur, but this is relative to the worst-case solution in the design space. Second, the “optimal” WWR is not a constant transferable. Recommendations in the included studies range from about 10% (2.6 m horizontal shading, tropical bilateral classroom, (Mangkuto et al., 2025) through 16-20% (synthesis of 31 Indian daylight studies, (Khaire et al., 2026) and 30-45% (tropical schools, Purnama et al., 2025) to 60% (slatted complex fenestration, Aritonang et al., 2025). In government schools, 20% WWR failed daylight criteria whereas 30-40% with shading performed well in Chennai (Jayaram et al., 2025) a direct conflict with the 16-20% range from the Indian synthesis explained by classroom depth, obstructions and metric choice. Hence the robust finding is not a number but a dependency. WWR must be optimized together with shading depth, orientation and room geometry for the specific site.

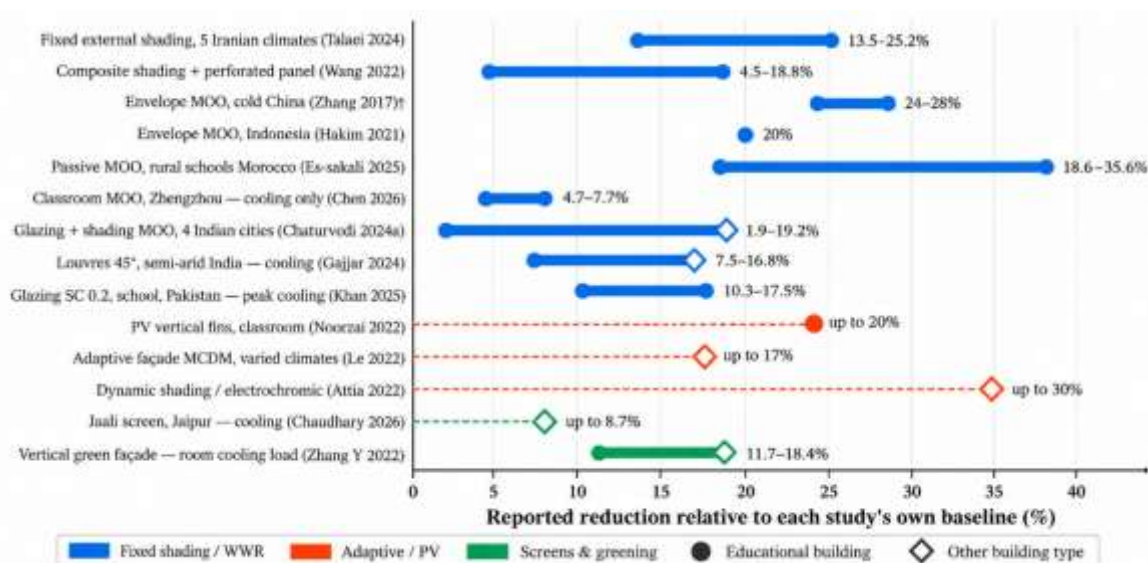


Figure 5. Facade interventions reported in included studies, energy or cooling load reductions.

4.2.2 Comfort criteria for naturally ventilated Indian classrooms

The common conclusion that emerges from the field studies in Indian classrooms is that the conditions that code bands assume in naturally ventilated classrooms are much cooler than students accept (refer Figure 6). In composite-climate secondary schools, 80% acceptability was: 15.3 °C to 33.7 °C, neutral temperature is at 27.1 °C (Jindal, 2018) and a year-long study suggested a range of 16-33.7 °C (Jindal, 2019). A comfort temperature of 29.8 °C was observed in university classrooms in composite climate (Singh et al., 2018) and ceiling fan usage was estimated to be more than 80% of the time when temperature is 29 °C (Kumar et al., 2018). As per the review of Indian naturally ventilated buildings, the range of the composite climate is 15.3-33.8 °C (Kaushal et al., 2024) and the IMAC family of adaptive models codifies this adaptability for offices and homes (Manu et al., 2016; Rawal et al., 2022). However, the National Building Code recommends a temperature range of 21-26 °C for all buildings (refer to Kumar et al., 2016).

There are two key requirements. The authors of the study which has been conducted in Dehradun (5297 primary pupils) state that the children were not comfortable because 94-100% of the samples were outside the acceptable range, despite the 95% saying they were satisfied, suggesting that children were not sensitive to the high temperatures but comfortable (Lala et al., 2022). Research elsewhere in the world suggests that hot classrooms are correlated with lower cognitive functioning (Manfren et al., 2026). For façade optimization, adaptive models should be calibrated for Indian occupants, therefore there is a need to cap the operative temperature for learning critical hours, and air speed should be treated explicitly as it extends the acceptable range by several degrees due to the use of fans (Kumar et al., 2016).

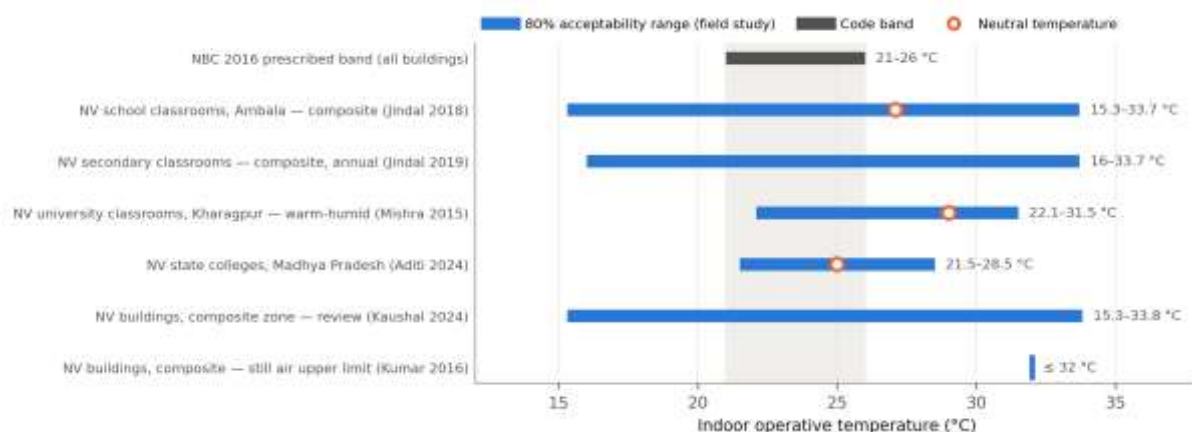


Figure 6. Thermal acceptability ranges reported for naturally ventilated classrooms and buildings in India compared with the NBCB.

4.2.3 Daylight, view and learning

There is correlational evidence that suggests that daylight quality in classrooms is related to learning outcomes. The daylight parameter that was most strongly associated with pupil test performance was window-to-floor ratio, for the European SINPHONIE sample (2,670 pupils, 155 classrooms) (Baloch et al., 2020). A cross-sectional study of 785 pupils found less stress and more focused behaviour in classrooms with more natural window views (Lindemann-Matthies et al., 2021), and a longitudinal Chinese study found sDA_{500,50%} correlated with students' daylight comfort and perceived productivity (Xu et al., 2025). The primary counter-risks are glare and sun patches on desks, and for this reason climate based metrics (sDA, ASE, UDI, DGP) are preferred over daylight factor which is still used in many Indian practices (Pastore et al., 2022, Ziaee et al., 2021). Studies in India are also limited in number for daylighting in schools, and simulation-based studies (Poptani & Parveen, 2022; Saxena et al., 2023) indicate that trees in the vicinity of the façade had a greater impact on daylight metrics than other factors such as orientation and floor level, highlighting the importance of accounting for site context in simulations.

4.2.4 Ventilation and indoor air quality

The façade is also the ventilation system in the case of naturally ventilated schools. A systematic review of 125 studies revealed that, across 2444 naturally ventilated primary classrooms, the median CO₂ concentration was 1487 ppm, with 81% of classrooms having CO₂ concentrations above 1000 ppm, and that there were consistent associations between increased CO₂ and higher rates of fatigue, absenteeism, and reduced performance (Honan et al., 2024). More windows reduces CO₂ but increases outdoor particulates and noise in the building, which is a critical issue in Indian cities. Little evidence exists in India regarding the classroom IAQ, and the information is not standardized (Kapoor et al., 2021a, 2021b). Optimising the effective opening area or ventilation is rarely a consideration of façade studies in the review, even though the same window needs to be optimised for all three.

4.2.5 Perforated screens (jaali)

There is quantitative evidence that Jaali screens are climate responsive, but none of it relates to schools, and they are also culturally appropriate as they are frequently described. In case of optimised Jaali configuration, the cooling demand during summer season was reduced by at least 8.71% and the optimum perforation ratio, screen thickness and cavity depth varied for different orientations for a Jaipur office building (Chaudhary et al., 2026). In New Delhi, (Debnath et al., 2026) found that the simulated annual cooling demand for a mycelium composite “bio-jaali” was 50.4% lower than that of a sandstone jaali, a result that is based on simulation and laboratory hygrothermal testing, but has not been validated in the field. The optimised perforated screens in hot climates resulted in a significant improvement of the UDI and a decrease in the EUI by up to 45% (Gaber et al., 2025). The evidence confirms that jaali is not a high performance element, but rather a variable to be optimised, and that, if poorly designed, a decorative jaali can prevent daylight entering into the the building, without providing any significant thermal performance.

4.2.6 Green façades

As can be seen from the experimental results, the external wall-surface temperatures under green façade are reduced by about 5-15 °C, where shading contributes about twice the evapotranspiration (Convertino et al., 2021, Bakhshoodeh et al., 2022). Vertical green façades were found to lower the cooling load of the rooms by 11.7-18.4%, which was more than the wall insulation (0.3-8.4%) in hot-summer climates by a co-simulation study (Zhang et al., 2022). In Vienna, a monitored school installation, 101 L/d evaporated from 58 m² of greening with a maximum difference in surface temperature of 11.6 °C (Salonen et al., 2022). The life-cycle picture is not as positive. An LCA analysis identified that a green façade (steel frame) was among the most burdensome wall options, with a green façade (timber frame) reducing the carbon footprint by 58%, but still outperforming aluminium or PVC sun-shading (Blanco et al., 2021). Irrigation demand in water stressed cities in India and maintenance in public schools are not covered in the evidence.

4.2.7 Adaptive and kinetic façades

Reviews report that the field is dominated by simulation and is focussed on offices with potential savings up to 40-70% in specific contexts (Usman et al., 2026) also that there are no large-scale experiments yet and that the field is short of such experiments (Gonçalves et al., 2024, Khraisat et al., 2024, Jamilu et al., 2024). Up to 17% reduction is reported (Le et al., 2022) and up to 30% for dynamic shading and electrochromic glazing (Attia et al., 2022) and there are very few applications reported in schools, primarily as design proposals (Fakourian et al., 2019; Al-Kazee et al., 2026). The benefits of well-designed fixed shading are likely to exceed capital cost, actuator maintenance and embodied impacts for Indian public schools were not tested in this study.

4.2.8 Life-cycle assessment and embodied carbon

The results of LCA studies indicate that energy efficiency optimisation for façade decisions can lead to higher WLC. The operational energy reduced by enhanced glazing was 8.3% (Feehan et al., 2021), whereas embodied carbon can be the significant contributor to the life-cycle balance since the service life of glazing is short (Gutai et al., 2024). About 33% more narrow double-skin façades raised product-stage (A1-A3) embodied carbon, but were the lowest in warm Japanese climates (Srisamranrungruang et al., 2026). Importantly, the best balance varies from place to place, six cities in the United States, an underinvestment in envelope efficiency on carbon-intensive grids costs more than 150 kgCO₂ e/m², while an overinvestment on clean grids costs more than 10 kgCO₂ e/m² (Echenagucia et al., 2022). Operational savings will be critical, as India's relatively carbon intensive grid implies, but that's an assumption that needs to be tested. In educational facilities, (Khan et al., 2025) found an LCA of façade materials reduced embodied carbon by 63.9% due to material substitution in a school in Peshawar, Pakistan; and exterior insulation systems (EIS) reduced LCEC by as much as 35% in Korean university retrofits (Liu et al., 2024). At the other end of the spectrum, rammed earth (285 kgCO₂e) and Hempcrete Timber (268 kgCO₂e, including biogenic storage) is a better option than concrete masonry (446 kgCO₂ e/m) (Alabdulrazzaq et al., 2026). All the reviews acknowledge that LCA is applied too late to impact design, and that there is no one LCA approach that is applicable to all design stages (Prideaux et al., 2024; Kumar et al., 2025; Huang et al., 2025).

4.2.9 Climate classification and climate-change resilience

The findings of climate zoning (Section 1.2) and the findings from future climate are both consistent with a single message. Facades for Indian schools should be tested with more than a single weather file. The school-stock studies show significant increases in the amount of overheating and in the impacts on cognitive performance by 2050, especially in lightweight single-sided, high glazing naturally ventilated classrooms (Manfren et al., 2026). The passive retrofit options (solar control, night ventilation, roof insulation) significantly reduce discomfort (Heracleous et al., 2021, Akkose et al., 2021); while reviews indicate that active cooling may be the only option in hot areas under future climate conditions (Liyanage et al., 2024). The analysis of 47 Mediterranean school cases revealed that the most common passive solutions are natural ventilation, green roofs, low-U windows and solar shading, while acoustic comfort and climate change adaptation and circular economy criteria are less commonly found (Díaz-López et al., 2022). In India, monitoring of climate responsive institutional buildings has shown that passive measures are effective, but that the effectiveness of these measures must be proven in their use (Manu et al., 2019).

4.2.10 Materials, durability and façade evolution

The typologies of facades have evolved from load bearing enclosure to multiple-layer systems designed to perform (Cucuzzella et al., 2023, Fernando et al., 2023, Tahmasbi et al., 2025). For schools in particular, (Al-Maliki et al., 2025) found that there was no local standard and long-term data on the durability of finishing materials in hot arid school façades, which will be further degraded by climate change (Athauda et al., 2023). There are many documented characteristics of the traditional Indian façade, but they are not related to measured performance. Linking this theme to LCA is the durability which forms the basis for the replacement cycles (EN 15978 module B4).

4.3 Summary of evidence by façade strategy

Detailed summary of evidence by façade strategy is given in table 3.

Table 3. Evidence on façade strategies that pertain to school buildings in composite transitional climates.

Strategy	Principal mechanism	Representative quantitative findings	Evidence strength*	Transferability to Pune schools
Orientation (long axis E-W)	Minimises E/W exposure to low-altitude sun	Rectangular south-oriented classrooms had lowest energy; N-facing gave most uniform desk-plane daylight (Alkhatatbeh et al., 2023)	Moderate (simulation, many climates)	High; consistent with solar geometry (Fig. 1)
WWR tuned per façade	Balances daylight and solar gain	Optima from 10% to 60% depending on shading and room depth; 20% failed daylight criteria in Chennai schools (Jayaram et al., 2025)	Moderate; context-dependent	Requires site-specific optimisation
Fixed external shading	Blocks direct beam before glazing	EUI -13.5% to -25.2% (Talaie et al., 2024); cooling -7.5% to -16.8% with 45° louvres (Gajjar et al., 2024)	Moderate-strong (simulation)	High; overhang S, fins E/W and N
Glazing (SHGC, VLT)	Controls transmitted solar and visible light	Peak cooling -10.3% to -17.5% with SC 0.2 glazing in a school (Khan et al., 2025); embodied penalty of advanced glazing (Gutai et al., 2024)	Moderate	Moderate; cost and embodied carbon trade-off
Perforated screen (jaali)	Partial shading, glare diffusion, privacy	Cooling up to -8.7% (Chaudhary et al., 2026); bio-jaali -50.4% (simulated; Debnath et al., 2026)	Weak-moderate; no schools	Promising; needs school testing
Green façade	Shading + evapotranspiration	Cooling load 11.7% to -18.4% (Zhang et al., 2022); high LCA burden with steel frames (Blanco et al., 2021)	Moderate (experimental)	Conditional on water and maintenance
Adaptive/kinetic façade	Time-varying solar control	Up to 17% to 30% (Le et al., 2022; Attia et al., 2022); few field tests (Gonçalves et al., 2024)	Weak for schools	Low for public schools at present
Operable openings (ventilation)	Air exchange, cooling by air movement	Median 1,487 ppm CO ₂ in NV classrooms; 81% >1,000 ppm (Honan et al., 2024)	Strong (large review)	Essential; rarely optimised with daylight

4.4 Cross-cutting methodological observations

There are four patterns that hinder the use of the evidence for design decisions. (i) Baseline heterogeneity improvements are reported relative to code, unshaded, average or worst-case baselines thus excluding pooling as shown in Figure 5. (ii) Metric heterogeneity: daylight as daylight factor (sDA), as UDI with different thresholds or as illuminance at points, comfort as PMV, adaptive models or as degree-hours. (iii) Limited validation: only a few simulation studies report calibration with measured data

and none of the Indian school façade studies are validation studies. (iv) Single-weather-file design: most of the studies rely on a typical meteorological year, but risk of overheating is extremely sensitive to future climate (Manfren et al., 2026). This is due to the main observations which do not warrant conducting a meta-analysis.

5. DISCUSSION

5.1 Answers to the research questions

RQ1. All of the above are well evidenced and consistently result in a reduction of energy or cooling loads of 2-36% from study baselines and an improvement in daylight for schools internationally, and are achieved during orientation, per-façade WWR, fixed external shading and glazing selection. Perforated screens and green façades have potential but have yet to be found in school practice or fields of evidence. RQ2. Appropriate adaptation criteria are those with comfort calibrations for Indian occupants (IMAC) with explicit air speeds, or with climate-based daylight metrics (sDA, ASE, UDI, DGP) and the band 21-26 °C is not a suitable optimisation target for naturally ventilated classrooms, and children's self-reported comfort should not be used alone as a justification for average high temperature. One of the objectives should be CO₂ or effective opening area. RQ3. Weak integration: no school study in India combines LCA and façade performance, though this combination is done in non-school studies (Feehan et al., 2021, Echenagucia et al., 2022, Srisamranrungruang et al., 2026), and in one school façade-materials study outside India (Khan et al., 2025). RQ4. The gaps are summarised in Table 4.

5.2 What is contested or overstated

Some statements, which are accepted as common knowledge in practice-oriented literature are weaker than they may seem. The above statement “Glass façades are not suitable for India” is broadly true for the physics but is specific to the glazing and/or the shading and/or the commercial building type; the question for the schools is the WWR -hading - glazing combination, not the glazing type. Traditional jaali would cause more comfort is based on perforation ratio, depth and orientation, it can also lower the daylight below the acceptable level (Chaudhary et al., 2026). There is no field validation of the use of kinetic façades in Indian public schools and no cost or maintenance considerations. Lastly, it is important to interpret comfort claims with caution when based on students' votes (Lala et al., 2022). It can also be argued that energy is not a primary issue in naturally-ventilated Indian schools as they use little electricity, the stronger argument for façade optimisation is indoor environmental quality, learning and heat resilience and carbon is a co-benefit which this review takes the position of.

5.3 Research gaps

Table 4. Research gaps identified and need for this research

Gap	Evidence from this review	Research need
G1 Integrated optimisation for Indian schools	12 of 94 studies concern Indian schools; none co-optimises energy, daylight, comfort and IAQ	Multi-objective optimisation of typical Pune classroom blocks with adaptive-comfort and climate-based daylight objectives
G2 Whole-life carbon	No Indian school study includes LCA; trade-offs depend on grid intensity (Echenagucia et al., 2022)	Coupled simulation-LCA (A1-A3, B4, B6) using Indian EPDs and grid factors
G3 Field validation	All Indian school façade studies are simulation-based	Monitored case studies (temperature, CO ₂ , illuminance) in Pune schools; model calibration
G4 Comfort criteria for children	Wide acceptability ranges; unreliable sensation votes (Lala et al., 2022)	Child-specific adaptive thresholds linked to cognitive or task outcomes
G5 Local and traditional elements	Jaali and green-façade evidence from offices or other climates	Parametric testing of jaali and greening on school façades, including water use and maintenance

Gap	Evidence from this review	Research need
G6 Climate classification and future climate	Five-zone scheme separates locations poorly; overheating rises by 2050	Location-specific and future (e.g., 2050) weather files for Pune; robustness testing of façade options
G7 Durability and maintenance	Limited data on finishing materials in school façades (Al-Maliki et al., 2025)	Service-life data for common Indian façade materials and their B4 impacts

5.4 Proposed integrated framework

G1-G7 is the answer from the proposed four-stage framework in figure 7. Stage 1 sets the context: existing weather data and weather data that could be morphed in the future, obstructions and sun path on site (Figure 1), school timetable and occupancy, and local materials. The design space for the façade is defined in Stage 2: orientation, WWR per façade, shading type and depth (overhangs, fins, jaali), U-value of the glazing, SHGC and VLT, wall assembly, finish and greening. Stage 3 evaluates each candidate based on the validated simulation: EUI and cooling demand, sDA, ASE, UDI and DGP, adaptive-comfort hours during school hours with explicit air speed, effective opening area or predicted CO₂. Stage 4: whole-life carbon (EN 15978 (CEN, 2011) - modules A1-A3 and B4 (where available) based on Indian environmental product declarations, and B6 on grid emission factors), life-cycle cost and maintenance and chooses the Pareto-optimal solutions with transparent multi-criteria decision-making (such as AHP or TOPSIS) based on stakeholder weights. The outcome of the above is fed into the second stage. Recommendations must be validated with monitored data from at least one existing Pune school before they can be generalised.

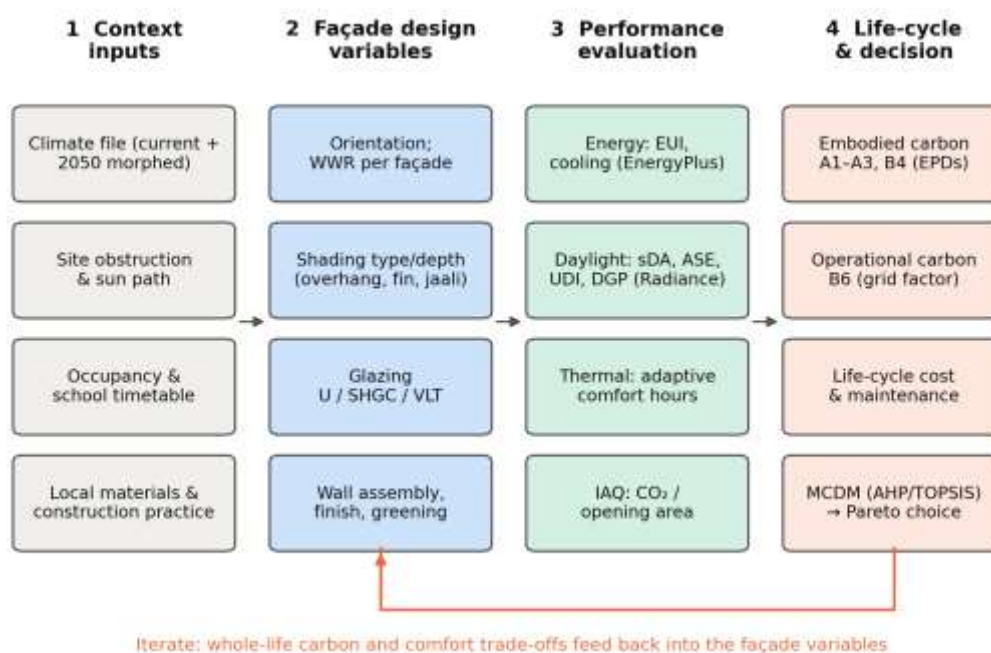


Figure 7. A suggested integrated performance life-cycle approach for the design of school façade for climate responsiveness in composite transitional climate is presented.

5.5 Implications for practice and policy

- The south/north and east/west façade of the building should be handled differently: horizontal shading on the south, small vertical fins on the north and vertical, egg-crate or perforated shading, with modest glazing on the east and west.
- WWR should be calculated with shading on the site, and should not be based on a fixed value as the calculated optimum is too variable.

- For naturally ventilated classrooms, the compliance for comfort should consider the adaptive criteria in conjunction with an upper limit on operative temperature during teaching sessions, provided the fan is used.
- Early-stage embodied-carbon estimates may need to be performed in tandem with energy and daylight assessments for options with regard to public school design.

6. CONCLUSIONS

The literature on climate responsive façades is vast, recent and in terms of its methodological approach, it is not in collaboration with the needs of Indian schools. Fixed shading, orientation and WWR-optimisation is well supported and the physics of Pune's sun path makes their application to the façade clear. Evidence from Indian classrooms suggests that code comfort bands are incorrect optimisation goals, though children's tolerance is not comfort. The real difference here is integration, no included study integrated Indian school façades to whole-life carbon and none validated façade performance in an occupied Indian school. This framework context, façade variables, validated multi-metric evaluation, whole-life carbon and transparent decision-making will be a testable pathway to evidence-based façade design for schools in Pune and similar composite/transitional climates. The next step is a monitored and calibrated case study of a representative Pune school block and then multi-objective optimisation with LCA for both current and 2050 weather condition.

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AUTHOR CONTRIBUTIONS

Kalyani Nilesh Junankar: Conceptualization, Methodology, Investigation, Data Curation, Writing: Original Draft.

Tarika Mohite Dagadkar: Investigation, Formal Analysis, Visualization, Writing: Review & Editing.

Gauri Shiurkar: Supervision, Data Curation, Validation, Visualization, Writing: Review & Editing.

Vikas Gulia: Project Administration, Writing: Review & Editing

CONFLICT OF INTEREST

The author declares no conflict of interest.

ETHICS STATEMENT

This study is a systematic review of published literature and did not involve human participants, animals, or the collection of personal data. Ethical approval and informed consent were therefore not required. This wording is accurate only if it matches how the work was done. The manuscript's own scope supports it.

DATA AVAILABILITY STATEMENT

The coded list of included studies and the search log are available from the author on request.

USE OF GENERATIVE AI

for literature search via Consensus, language editing, figure generation from Claude.AI), and confirm that the author verified all content and takes full responsibility.

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