Quantifying Thermal Leakage and Passive Cooling Efficiency in Low-Cost Urban Housing

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ABSTRACT

Dense, minimum-cost urban housing dominates South Asian cities, and much of it performs poorly under thermal load. This paper synthesizes existing field-study and engineering literature to quantify how heat enters low-cost urban dwellings in India and to evaluate which passive cooling interventions produce measurable, reproducible indoor temperature reductions. Drawing on peer-reviewed field trials, government reports, and simulation studies, the review finds that roof-level interventions deliver the largest single-point gains: reflective coatings lower peak indoor temperature by roughly 1-5°C, and combined coating-plus-insulation retrofits achieve 6-13°C reductions over uninsulated metal sheeting. Wall material substitution and improved ventilation contribute smaller but meaningful gains, roughly 2-4°C and up to 3.9°C respectively, with ventilation also cutting discomfort-hours by 22-78%. Findings are organized within a conduction-convection-radiation framework and weighed against cost-accessibility for low-income households. The central conclusion is that no single retrofit suffices alone; the largest, most equitable gains come from layering a low-cost reflective roof with a modest ventilation upgrade.

KEYWORDS: *Passive Cooling, Thermal Leakage, Low-Cost Urban Housing, Thermal Comfort, Cool Roofs, Natural Ventilation, Heat Transfer, Energy Efficiency, Informal Settlements, South Asian Urban Climate.*

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1. INTRODUCTION

On a May afternoon in Ahmedabad or Mumbai, outdoor temperatures regularly exceed 40°C, yet indoors, a tin- or asbestos-roofed informal dwelling is often hotter still. Roughly one billion people worldwide live in informal or low-cost housing, heavily concentrated in South Asia's densifying cities, where heat waves are growing longer and more lethal. Such housing typically relies on thin, high-conductivity materials, including corrugated metal or asbestos-cement roofing, single-leaf brick walls, and minimal window openings, chosen for affordability and speed rather than thermal performance. The structure meant to provide shelter instead amplifies the environment it should buffer, absorbing solar radiation through the roof by day and re-radiating that heat indoors well into the night.

This is not merely a comfort problem but a public-health and economic one. Elevated indoor heat is linked to disrupted sleep, reduced productivity, illness, and excess mortality, with the burden falling hardest on households least able to afford cooling. As room air conditioner penetration rises across Indian cities, the resulting electricity demand strains grids and intensifies the very urban heat island effect that made cooling necessary in the first place. A scalable, passive solution that reduces heat gain through the envelope rather than mechanically removing it afterward is therefore both an engineering and a developmental priority.

This paper's objective is focused: to consolidate, from existing published evidence, how much measurable thermal benefit specific low-cost passive interventions deliver in South Asian low-income housing, and to map these benefits to the heat-transfer mechanism each one targets. Rather than generating new data, the study synthesizes field trials, government technical reports, and simulation studies from Indian cities, principally Ahmedabad, Mumbai, and Jaipur, into a comparative, physics-grounded reference for designers, NGOs, and municipal heat-action planners working under tight cost constraints.

2. Literature Review

The literature on passive cooling for low-cost South Asian housing clusters around three structural targets: roofs, walls, and ventilation pathways. It is dominated by field studies from Ahmedabad and Mumbai, where municipal heat action plans have driven applied research since the early 2010s.

2.1. Roof-Level Interventions: The Dominant Research Focus

Roofs receive disproportionate research attention because they intercept the largest share of incident solar radiation in low-storey informal housing. The most documented intervention is the solar-reflective ("cool roof") coating, typically a white lime-wash or acrylic paint applied over existing tin, asbestos, or concrete roofing. A cross-sectional study across sixteen slum households in Ahmedabad compared four roof-level retrofits, namely a bio-composite panel (Modroof), reflective white paint, a ventilated air-gap panel (Airlite), and a Thermocol false-ceiling, against unmodified tin, asbestos-cement, and concrete controls, finding statistically significant indoor-temperature reductions for all four. Program-scale rollouts building on this pilot report that coatings alone lower indoor temperature by roughly 2-5°C versus uncoated sheeting, while combining a coating with an insulating underlayer such as Thermocol or bamboo-jute roughly doubles this benefit, yielding 6-13°C reductions against a bare tin baseline.

A separate experimental strand reports that white-coated corrugated steel achieves up to 34% surface-temperature reduction versus uncoated material, with fiber-cement and terracotta surfaces showing smaller 18-25% gains. Simulation of a 50 m² reflective roof projected a 26-49% reduction in cooling energy consumption, reinforcing roofs as the largest single leverage point in the envelope.

2.2. Wall Materials: A Comparatively Under-Studied Gap

Wall-level research is thinner and more fragmented than roof research, despite walls representing a large envelope area in multi-storey housing. Most data comes from materials-industry comparisons rather than controlled field trials, which is a notable gap. Reviews of low-cost Indian wall materials report that fired clay brick has comparatively high conductivity ($U \approx 1.4$-1.7 W/m²K), a poor insulator, whereas AAC blocks and fly-ash bricks, increasingly used in PMAY-linked affordable housing, insulate better through entrained air pockets and lower density. Reported AAC cooling-energy savings range from roughly 15-20% in warm-humid coastal cities to 25% in hot-dry inland cities, though these figures derive mostly from industry case studies rather than independent field measurement. Vernacular mud and earthen-block construction is reported in isolated studies to cut cooling-related energy use by as much as 50% through high thermal mass, but this evidence is sparse and rarely benchmarked against a consistent control.

2.3. Ventilation Geometry: Strong Simulation Evidence, Limited Field Validation

Ventilation research relies heavily on CFD and EnergyPlus modelling rather than informal field comparison. A CFD and energy-modelling study of architect Charles Correa's low-income housing prototype for hot-arid India found optimized cross-ventilation reduced operative temperature by up to 3.1°C on the hottest day and 3.9°C on a typical cooling day, cutting discomfort hours by 31.3% and 77.8% respectively. Spot-monitoring and EnergyPlus simulation in Mumbai's Dharavi found true cross-ventilation or a 15 cm roof air gap reduced overheating hours by 22-39%, with zero electricity input. A CFD-validated Jaipur hostel study measured a more modest 2.0-2.5°C drop from night ventilation. Adaptive comfort surveys in naturally ventilated Mumbai housing found occupants' acceptable comfort band (24.6-32.2°C) considerably wider than standard ASHRAE or NBC thresholds, suggesting fixed comfort models may understate ventilation's practical value here.

2.4. The Core Gap This Paper Addresses

Three gaps recur. First, almost no study compares roof, wall, and ventilation interventions against a common baseline using a common metric: some report °C drop, others percentage energy or discomfort-hour reduction, which complicates synthesis. Second, cost data is reported inconsistently or omitted, even though cost-per-degree-of-cooling is what actually matters to a low-income household. Third, wall-level interventions remain under-tested in occupied housing relative to roofs and ventilation. This synthesis targets the first two gaps directly by standardizing reported outcomes onto a common comparative basis and foregrounding cost wherever available.

3. Theoretical Framework

Heat gain inside a low-cost dwelling is governed by the simultaneous action of conduction through the envelope, convective exchange between surfaces and air, and radiative exchange with the sun and sky. The relationships below frame the interpretation of results in Section 5.

3.1. Conductive Heat Transfer Through the Envelope

Steady-state conductive heat flux through a roof or wall follows Fourier's law:

$$q = U \cdot A \cdot \Delta T$$

where q is heat transfer rate (W), U is overall thermal transmittance (W/m²K), A is surface area (m²), and ΔT is the temperature difference across the assembly. U is the reciprocal of total thermal resistance:

$$U = 1 / R\_total = 1 / (R_1 + R_2 + \dots + R\_n)$$

with each R_i = L_i / k_i for a layer of thickness L and conductivity k. This explains why thin, single-leaf metal or asbestos roofing (high k, low L, hence high U) transmits heat readily, and why substituting a lower-k wall material such as AAC directly reduces U and therefore q.

3.2. Convective Heat Exchange and Ventilation

Convective exchange at a surface follows Newton's law of cooling:

$$q\_conv = h \cdot A \cdot (T\_s - T\_air)$$

where h is the convective heat transfer coefficient (W/m²K), which rises with air velocity. This is the physical basis for cross-ventilation: faster indoor air raises h at the body and surface boundary layer, increasing heat removal even when air temperature itself changes only modestly. This is also why ventilation's comfort gains can exceed what temperature reduction alone predicts.

3.3. Radiative Heat Gain at the Roof Surface

Radiative exchange between a roof and the sun/sky combines absorbed irradiance with the Stefan-Boltzmann relation:

$$q\_rad = \alpha \cdot G + \varepsilon \cdot \sigma \cdot (T\_s^4 - T\_sky^4)$$

where α is solar absorptivity, G is incident irradiance (W/m²), ε is emissivity, σ is the Stefan-Boltzmann constant, and T_s, T_sky are surface and effective sky temperature. Reflective coatings work by lowering α, typically from 0.6-0.9 for dark, uncoated metal down to 0.2-0.3 for white acrylic or lime coatings, which directly cuts absorbed radiation. This is the dominant mechanism behind the reductions reported in Section 2.1.

3.4. Combined Envelope Model and Cooling Load

Total instantaneous heat gain combines all three mechanisms across the envelope, determining the sensible cooling load Q_load an active system would otherwise remove:

$$Q\_load = \Sigma(U\_i \cdot A\_i \cdot \Delta T\_i) + \Sigma(q\_rad,i) + Q\_vent + Q\_internal$$

where Q_vent is net sensible heat exchanged via ventilation and Q_internal represents occupant/appliance gains. This model explains why roof interventions, which affect both the U and α terms simultaneously, outperform single-mechanism interventions, and why layering interventions across mechanisms (reflective roof plus ventilation) produces roughly additive rather than redundant gains.

4. Methodology

This study adopts a structured literature-synthesis methodology rather than original field measurement or simulation, consolidating dispersed, heterogeneously reported findings into one comparative framework. The methodology follows four stages: search strategy, screening/inclusion criteria, data extraction and standardization, and synthesis logic.

4.1. Search Strategy

Literature was identified through structured searches of ScienceDirect, PubMed/PMC, Springer Nature, ResearchGate, and institutional reports (MoEFCC Ozone Cell; Alliance for an Energy Efficient Economy; Mahila Housing SEWA Trust). Search terms combined a housing-context term (“low-cost housing”, “slum”, “affordable housing”, “informal settlement”) with a thermal-performance term (“passive cooling”, “thermal comfort”, “cool roof”, “natural ventilation”, “U-value”) and a regional qualifier (“India”, “Ahmedabad”, “Mumbai”, “South Asia”). Searches were restricted to English-language material.

4.2. Inclusion and Exclusion Criteria

Sources were included if they met all of the following:

- Reported a quantitative thermal outcome, such as indoor temperature change, cooling-load/energy change, or discomfort-hour change, attributable to a specific, identifiable intervention or baseline material.
- Concerned low-cost, affordable, or informal urban housing, or a directly analogous typology (slum dwellings, PMAY-category housing).
- Was set in, or explicitly modelled on, a South Asian climate, with priority given to Indian cities; a small number of broader tropical studies were retained only to fill mechanism-level gaps (e.g., ventilation geometry) where India-specific data was insufficient.

Sources were excluded if they:

- Addressed only qualitative perception without a paired quantitative outcome.

- Concerned high-rise commercial or luxury housing irrelevant to low-cost typologies or materials.
- Could not be traced to an identifiable primary measurement, simulation, or peer-reviewed source.

4.3. Data Extraction and Standardization

For each source, the following fields were extracted where available: intervention type and category (roof, wall, ventilation, or combined), comparison baseline, reported outcome and original unit, climate/city context, study method (field measurement, CFD/EnergyPlus simulation, or controlled experimental rig), sample size or scope, and cost where stated. Outcomes are reported in inconsistent units, including absolute °C drop, percentage cooling-energy reduction, percentage discomfort-hour reduction, and percentage surface-temperature reduction, so this paper does not force a single converted unit across all studies, since doing so would require unstated assumptions about baseline cooling-degree-days, envelope area, or occupancy. Instead, outcomes are grouped by mechanism category and reported in original units side by side, with a qualitative magnitude ranking (low/moderate/high) applied consistently across categories. This prioritizes transparency over manufactured comparability.

4.4. Synthesis Logic

Findings were synthesized in two stages. First, results within each category (roofs, walls, ventilation) were aggregated to identify a representative range, noting outliers and the methodological factors, such as field versus simulation, sample size, and climate zone, likely explaining within-category variation. Second, results were cross-referenced against Section 3 to attribute each outcome to its dominant heat-transfer mechanism (e.g., coatings to the radiative absorptivity term, ventilation to the convective coefficient term), supporting the Section 6 argument that combining interventions across mechanisms should produce additive rather than overlapping benefit. Where a single study reported multiple intervention types against the same control (e.g., the Ahmedabad cross-sectional study), its internal ranking was treated as higher-confidence evidence than cross-study comparison, since it eliminates inter-study confounds like differing climate or protocol.

All cost figures are reported in Indian Rupees or as relative/percentage terms exactly as stated in source material; no currency conversion or inflation adjustment was applied, and absolute cost figures should be read as indicative of order-of-magnitude rather than precise present-day pricing.

5. Results

This section presents synthesized comparative outcomes across the three intervention categories: roofs, walls, ventilation, followed by a cross-category summary.

5.1. Roof-Level Interventions

Table 1 summarizes indoor temperature outcomes for roof-level interventions from the Ahmedabad field trials and related Indian cool-roof program data.

Intervention	Baseline Compared Against	Reported Outcome	Evidence Source/Type
Solar-reflective white coating (lime/acrylic)	Bare tin / asbestos sheet roof	1–5°C indoor temp. reduction	Multi-city field trials (4 Indian cities)
Reflective coating + Thermocol/bamboo-jute layer	Bare tin roof (uninsulated)	6–13°C indoor temp. reduction	Field trials, combined treatment
Thermocol false ceiling beneath asbestos	Tin / asbestos / concrete (control)	Statistically significant reduction ($p < 0.05$)	Ahmedabad 16-household field study
Modroof (coir/paper-waste composite panel)	Tin / asbestos / concrete (control)	Significant reduction vs. controls	Ahmedabad 16-household field study
Airlite ventilated roof panel	Tin / asbestos / concrete (control)	Moderate reduction vs. controls	Ahmedabad 16-household field study
White-coated corrugated steel (lab/experimental)	Uncoated corrugated steel	Up to 34% surface temp. reduction	Controlled experimental roof rig
Reflective roof, cooling-load simulation (50 m²)	Uncoated opaque roof, $T_0 = 60°C$	26–49% cooling energy reduction	Simulation study

Table 1. Roof-level passive cooling interventions and reported thermal/energy outcomes.

The pattern is consistent: every roof intervention tested against an unmodified baseline produced a measurable reduction, and combining a reflective treatment with an insulating layer roughly doubles the benefit of the coating alone. This is consistent with Section 3, since coatings reduce the radiative term (α·G) while an insulating layer independently reduces U, acting on largely separate terms in the combined heat-gain equation.

5.2. Wall-Level Interventions

Material	Reported Thermal Conductivity / Outcome	Comparative Note	Evidence Type
Fired clay (red) brick	k → U ≈ 1.4–1.7 W/m²K (high)	Baseline; poor insulator, conventional default	Materials comparison review
Fly-ash brick	Moderate insulation; ~20% lower cement use, ~18 t soil saved per lakh bricks	Improves on red brick; byproduct material	Materials review / industry data
Autoclaved Aerated Concrete (AAC) block	Reported 15–25% annual cooling energy savings (climate-dependent)	Best-performing manufactured low-cost block	Industry-reported case data
Mud / adobe / earthen block (vernacular)	Reported up to ~50% annual cooling-energy-use reduction	High thermal mass; sparse, scattered field evidence	Isolated field studies
Coconut/basalt fiber-reinforced composite block	~17.4% improvement in thermal insulation performance	Emerging material; limited deployment scale	Materials science study

Table 2. Wall material thermal performance comparison (data quality more heterogeneous than Table 1; see Sections 2.4 and 6.2).

Wall results show a wider performance range than roof results but rest on a thinner, more industry-reported evidence base. AAC substitution for red brick is the most consistently documented improvement, with savings of 15-25% depending on climate zone. Vernacular mud/adobe shows the largest reported benefit but the thinnest supporting evidence; its 50% figure should be read as an upper-bound case, not a representative average.

5.3. Ventilation-Geometry Interventions

Intervention	Context / Method	Reported Outcome	Evidence Type
Optimized cross-ventilation (Charles Correa LIH prototype)	Hot-arid Indian climate; CFD + energy model	3.1°C drop (peak day); 3.9°C drop (typical day)	CFD + building energy simulation
Discomfort-hour reduction, same study	Same prototype, two scenarios	31.3% (peak day); 77.8% (typical day) fewer discomfort hours	CFD + building energy simulation
Cross-ventilation / 15 cm roof air gap	Mumbai (Dharavi), EnergyPlus + spot monitoring	22–39% reduction in overheating hours	Simulation + field spot-check
Night ventilation strategy	Jaipur composite climate, hostel building	2.0–2.5°C air temperature drop	CFD (validated against field measurement)
Optimized interior layout for natural ventilation	Mumbai low-income tenement, CFD + energy modelling	364 kWh/year cooling energy saved (~INR 2,576/year)	CFD + cost-modelling study

Table 3. Ventilation-geometry interventions and reported thermal/comfort/energy outcomes.

Ventilation shows smaller absolute temperature reductions than the best roof treatments but disproportionately larger comfort gains, since faster air raises the convective coefficient h at the occupant boundary layer (Section 3.2), improving perceived comfort even when bulk temperature falls only modestly. This aligns with the wider adaptive comfort band (24.6-32.2°C) found among Mumbai occupants, suggesting standard comfort models may understate ventilation's practical value for this population.

5.4. Cross-Category Comparison

Ranking interventions by typical indoor temperature impact (using range midpoints): combined reflective-coating-plus-insulation roof retrofit (6-13°C) > coating alone (1-5°C) ≈ wall substitution to AAC or vernacular earthen construction (15-50% cooling-energy-equivalent, no direct °C figure) > optimized ventilation geometry (2.0-3.9°C, with disproportionately larger comfort-hour gains). The most consistent finding across all three categories is that no single-mechanism intervention closes the full gap between unmodified low-cost housing and acceptable thermal comfort during peak heat events; the largest reported gains in the literature consistently come from studies layering interventions across mechanisms, such as a reflective coating combined with insulation, or cross-ventilation combined with a shaded or reflective roof.

6. Discussion and Limitations

6.1. Real-World Scalability

The strongest case for scalability is the reflective roof coating. It requires no structural modification, can be applied by minimally trained labor with a brush or roller, uses materials already available in most Indian cities, and has been deployed at program scale: Ahmedabad's municipal cool-roof initiative expanded from a pilot to cover more than 15,000 slum roofs and 1,000 government buildings. This combination of low skill requirement, low cost, and demonstrated municipal-scale deployment makes reflective coating the most “shovel-ready” intervention identified here. Ventilation improvements are similarly scalable in new construction, where window placement and cross-ventilation paths cost little to design in, but are far harder to retrofit into dense informal settlements where adjacent structures and fixed party walls physically block ventilation paths regardless of an individual household's intent. Wall material substitution is the least scalable for existing housing, since it generally requires reconstruction rather than retrofit. This makes it relevant mainly to new affordable-housing construction (PMAY-category projects) rather than the existing informal stock bearing the greatest thermal burden today.

6.2. Cost-Benefit Considerations for Low-Income Residents

Cost data in the literature is uneven, but available figures suggest a clear hierarchy. Reflective coatings are reported in Indian program contexts as costing a small fraction of a typical household's monthly income per roof, requiring reapplication only every few years, which gives a strongly favorable cost-per-degree ratio. Insulating layers (Thermocol, bamboo-jute) add incremental cost but can roughly double the achieved reduction, a favorable marginal return for households that can afford the outlay. Wall upgrades to AAC carry the highest upfront cost, applying only at new-construction stage and requiring full masonry replacement. This puts them out of reach for incremental household retrofit and squarely within the domain of government schemes like PMAY. Ventilation improvements are essentially free at the design stage but costly or physically impossible to retrofit into existing dense settlements, raising an equity concern: households most exposed to extreme indoor heat, namely those in the densest, oldest informal settlements, are often the ones for whom the cheapest-in-theory intervention is least achievable in practice.

6.3. Limitations of This Synthesis

Several limitations qualify these conclusions. First, the underlying studies use inconsistent outcome metrics (°C, percentage energy, percentage discomfort-hours), and the decision not to force-convert between them (Section 4.3) means the Section 5.4 ranking is qualitative rather than strictly quantitative. Second, evidence density is uneven: roof interventions rest on multiple field studies with programmatically validated samples, while wall-material evidence relies more on industry-reported figures not independently replicated under controlled conditions, warranting lower confidence. Third, most higher-quality field evidence comes from a small number of Indian cities (Ahmedabad, Mumbai, Jaipur), and climate-zone differences between hot-dry, warm-humid, and composite conditions mean results cannot be assumed to transfer uniformly across South or Southeast Asia without local validation. Fourth, this study does not independently re-derive any synthesized figures; it inherits the measurement and reporting limitations of the original sources, including the small sixteen-household sample of the most detailed Ahmedabad study. Finally, a physical temperature reduction of even several degrees does not translate linearly into comfort or health benefit; the relationship is non-linear and shaped by humidity, air movement, and physiological adaptation, so the °C figures here should be read as engineering performance indicators rather than direct proxies for health or wellbeing improvement.

7. Conclusion

This synthesis yields one clear quantitative takeaway: roof-level reflective coatings, particularly paired with a thin insulating layer, deliver the largest and most consistently documented indoor temperature reductions among low-cost passive interventions, at 1-5°C for a coating alone and 6-13°C combined with insulation, and at a cost and skill threshold low enough for municipal-scale deployment in informal settlements. Ventilation improvements deliver smaller absolute reductions (roughly 2-4°C) but disproportionately large comfort gains (up to 78% fewer discomfort hours in optimized simulations), making them a high-value complement wherever physically retrofittable. Wall upgrades show the largest theoretical percentage gains but the thinnest evidence base, realistically restricted to new-construction housing rather than existing informal stock.

Three recommendations follow. First, municipal heat-action programs should prioritize reflective-roof-coating rollout as the default first-line intervention for existing informal housing, given its demonstrated cost-effectiveness and Ahmedabad's program-scale precedent. Second, coating programs should budget for a low-cost insulating underlayer as a second-phase upgrade, since this roughly doubles thermal benefit for modest added cost. Third, ventilation-geometry standards, including minimum cross-ventilation pathways, window-to-wall ratios, and roof air-gap allowances, should be written into affordable-housing design codes at the new-construction stage, since retrofitting ventilation into dense existing settlements is far costlier and often infeasible compared to designing it in from the outset. Future research should prioritize closing the wall-material evidence gap through controlled field trials comparable in method to the Ahmedabad roof studies, and adopt a standardized outcome-reporting metric to make future cross-study synthesis more rigorous than was possible here.

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