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LOW CARBON • CLIMATE RESILIENT • CITY DEVELOPMENT

Heat Resilience in Buildings

A Practitioner's Guidebook



Acknowledgement and Disclaimer

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List of Abbreviations

AAC	Autoclaved Aerated Concrete
AC	Air Conditioner / Air Conditioning
ACH	Air Changes per Hour
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BCA	Building and Construction Authority (Singapore)
BEE	Bureau of Energy Efficiency
BLDC	Brushless Direct Current (fan motor)
BMS	Building Management System
CEEW	Council on Energy, Environment and Water
CSEB / ICSEB	(Interlocking) Compressed Stabilised Earth Block(s)
DX	Direct Expansion
ECBC	Energy Conservation Building Code
ECSBC	Energy Conservation and Sustainable Building Code
ENS	Eco-Niwas Samhita
EPA	Environmental Protection Agency (US)
EPDM	Ethylene Propylene Diene Monomer (roofing membrane)
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GRIHA	Green Rating for Integrated Habitat Assessment
HAP	Heat Action Plan
HDPE	High-Density Polyethylene
HEV	Hazard, Exposure and Vulnerability (framework)
HVAC	Heating, Ventilation, and Air Conditioning
ICAP	India Cooling Action Plan
IGBC	Indian Green Building Council
IGU	Insulated Glazing Unit
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
LEED	Leadership in Energy and Environmental Design
LST	Land Surface Temperature
NBC	National Building Code (of India)
NDMA	National Disaster Management Authority
NDVI	Normalized Difference Vegetation Index
NEA	National Environment Agency (Singapore)
NParks	National Parks Board (Singapore)
NRF	National Research Foundation (Singapore)
PCM	Phase Change Material
PVC	Polyvinyl Chloride
RCC	Reinforced Cement Concrete
SDRF	State Disaster Response Fund
SHGC	Solar Heat Gain Coefficient
SRI	Solar Reflectance Index
TPO	Thermoplastic Olefin (roofing membrane)
UHI	Urban Heat Island
ULB	Urban Local Body
URA	Urban Redevelopment Authority (Singapore)
VIP	Vacuum Insulation Panel
VLT	Visible Light Transmittance
VRF	Variable Refrigerant Flow
WWR	Window-to-Wall Ratio



Executive Summary

Rising urban temperatures are no longer a future risk for Indian cities; they are a present reality. India's annual mean temperature has already increased by 0.15°C per decade since 1951, and extreme heat now threatens health, livelihoods, and infrastructure at scale. Reduced labour productivity from heat could cost India 35 million jobs and 4.5% of its GDP by 2030. With more than 40% of the country's population projected to live in cities by then, and the built-up area across its largest metros nearly doubling between 1995 and 2025, the built environment sits at the centre of this challenge.

Buildings both contribute to and help reduce heat stress. Poor design, dense construction, and heat-retaining materials such as concrete and asphalt have moved buildings away from the vernacular principles, thick walls, courtyards, shaded openings, that once kept them adapted to South Asia's hot-dry and warm-humid climates. This has pushed many buildings toward energy-intensive air conditioning to maintain comfort, straining electricity grids and deepening a self-reinforcing cycle of heat, energy demand, and GHG emissions.

Yet, well-designed buildings remain one of the most effective buffers against heat stress, particularly for vulnerable groups, the elderly, outdoor workers, and residents of informal settlements, for whom a building's ability to stay cool passively can be a matter of health and survival, not just comfort.

This guidebook helps urban stakeholders understand the challenges in modern building design and construction practices and apply practical solutions appropriate to their local climate. It covers how urban form, street geometry, surface materials, and green-blue infrastructure shape the baseline heat conditions a building must contend with, and why building design and city-level planning must work together.

India's Hot-Dry, Warm-Humid, and Composite climate zones cover over 75% of its land area and urban population. Since building design strategies that work in one zone may not work in another, such designs must be tailored to local climate, geography, and material availability.

Heat resilience is most cost-effective when passive design and material selection are addressed correctly first, as they reduce the underlying heat load at little or no added cost. Nature-based solutions and, where necessary, active mechanical cooling should then complement these measures.

The guidebook presents heat resilience strategies covering passive cooling strategies (form, orientation, shading, ventilation), climate-responsive building materials (walls, roofs, insulation, glazing), active cooling solutions (fans, HVAC, radiant systems) sized to complement passive design, and nature-based solutions (green roofs, vertical gardens, tree shading, water bodies) that cool at both the building and precinct scale.

The guidebook also provides an overview of key mandatory and voluntary codes and standards, such as Energy Conservation Building Code, Energy Conservation and Sustainability Building Code, Eco-Niwas Samhita, National Building Code, that urban stakeholders and practitioners can use through local building byelaws. It also explains how Heat Action Plans (HAPs) and building codes complement each other, with HAPs helping cities identify the highest-risk areas to plan and implement heat resilience interventions while building codes and standards help improve thermal performance of new buildings.

Success stories of microclimate-sensitive planning and heat-resilient building design at both neighbourhood-scale and building-scale are presented as examples. Many of the interventions covered in this guidebook can be encouraged or mandated through existing planning permissions, building byelaws, and municipal greening programmes without requiring new legislation, offering cities a practical pathway to build more heat-resilient cities.



01 Introduction

1.1 | Background

The urban built environment in rapidly growing South Asian cities is experiencing rising temperatures due to global climate change and several compounding local factors. Cities undergoing rapid urbanisation have become vulnerable to heat stress due to high construction density, limited green spaces, surfaces with low reflectivity, and the extensive use of heat-retaining building materials such as concrete and asphalt. These factors, combined with reduced natural ventilation pathways due to poor urban planning and waste heat from vehicles and industrial activities, have led to a localised urban heat island (UHI) effect, in which densely built areas, such as city centres, record significantly higher temperatures than surrounding peripheral or rural areas.

Modern buildings have played a key role in contributing to localised heat stress, as building design and construction practices have moved away from vernacular principles that historically enabled buildings to adapt to hot-humid and hot-dry tropical climates, prevalent across South Asia. Vernacular building design elements such as thick walls, courtyards, high ceilings, shaded openings, and use of locally sourced, low-conductivity materials have largely been replaced by glass facades, concrete structures, and compact floor plans that are ill-suited to the region's tropical climate.

Even so, buildings act as critical buffers against heat stress by ensuring thermal comfort for people, especially during extreme heat events such as heat waves, which are becoming increasingly frequent and intense during summer. A building envelope consciously designed with passive cooling elements can significantly reduce indoor temperatures, reducing occupants' exposure to heat stress when outdoor conditions become hazardous due to extreme heat. This role is particularly critical for vulnerable groups, such as the elderly, people with pre-existing health conditions, outdoor workers, and residents of informal settlements, who have limited access to cooling infrastructure and are more susceptible to heat stress-induced health risks. Consequently, the ability of their buildings to passively moderate indoor temperatures become not just a matter of thermal comfort but one of public health and survival. Poor building design and orientation, together with lack of passive cooling measures, have increased heat ingress into buildings, compromising the thermal comfort they can provide. As a result, indoor thermal comfort is often achieved through energy-intensive air-conditioning systems rather than passive or low-energy building design strategies, leading to a sharp rise in building energy consumption, and further straining the power grid already burdened by rising peak load demand during hot, sunny days. This creates a vicious cycle in which heat stress increases cooling demand, leading to higher energy consumption and peak electricity loads, which in turn contribute to further warming through waste-heat rejection and, where electricity grids remain fossil-fuel dependent, higher greenhouse gas (GHG) emissions.

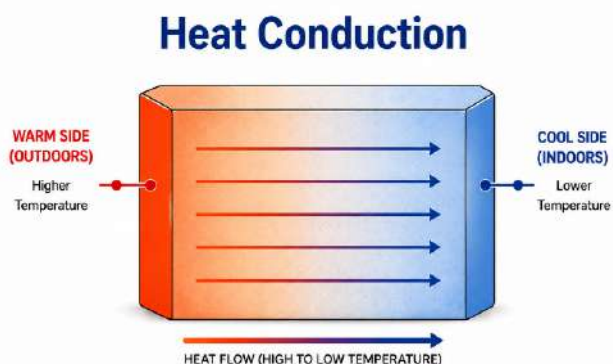
Given the compounding risks and impacts of climate change, it is imperative for buildings to enhance their heat resilience through climate-responsive design, passive cooling strategies, and the integration of nature-based solutions (NbS), reducing both heat vulnerability and energy demand while safeguarding occupant health and comfort.



1.2 | Heat Dynamics in the Built Environment

Heat Transfer Mechanisms: Heat ingress from the hot outdoor environment into a building occurs through three modes of heat transfer, conduction, convection, and radiation. These mechanisms determine how heat is gained, stored, transferred, and dissipated in a building and affect thermal, visual comfort, and energy efficiency. The three heat transfer mechanisms are explained briefly below:

Conduction refers to heat transfer through solid materials, such as walls and roofs, where heat flows from a region of higher temperature (e.g., external wall surfaces) to one of lower temperature (e.g., interior wall surfaces).



Heat absorbed by a Reinforced Cement Concrete (RCC) roof being conducted into the indoor space is an example of conduction contributing to heat ingress in buildings.

Heat transfer through conduction depends on the material's thermal conductivity (k), its thickness (Δx), surface area (A), and the temperature difference (ΔT) between the hot and cold regions. It is governed by the following equation:

$$\text{Rate of heat conduction, } Q_{\text{cond}} = kA(\Delta T / \Delta x)$$

Building materials such as concrete and metal sheets with high thermal conductivity transfer heat rapidly, causing a quicker rise in indoor temperatures, whereas materials such as wood and insulation boards conduct heat slowly, leading to a relatively slower rise in indoor temperatures. Figure 1 compares the thermal conductivity of some common building materials.

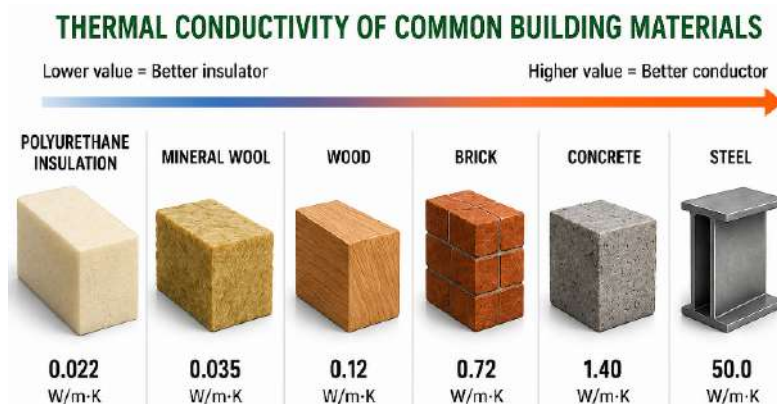


Figure 1: Thermal conductivity of common building materials
[Source: ASHRAE Handbook – Fundamentals (2017)¹]

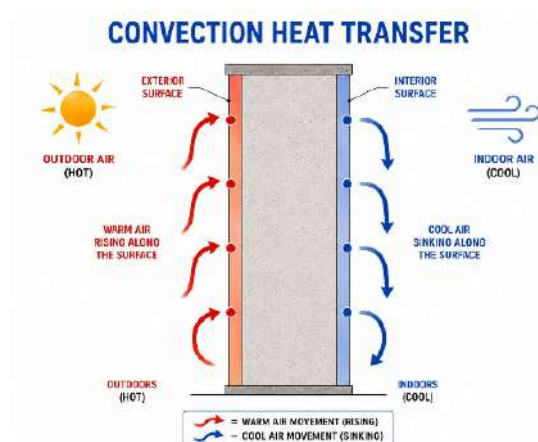
Convection is the transfer of heat through the movement of fluids, such as air or water, across a surface. Heat flows from a heated surface to the moving fluid, or vice versa. Heat transfer from a hot roof to the surrounding outdoor air and from warm indoor air, rising and moving across an interior wall surface, are examples of how convection contributes to heat gain and heat distribution in and around buildings.

¹ ASHRAE (2017). American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) handbook: Fundamentals.



Heat transfer through convection depends on the convective heat transfer coefficient (h), which is influenced by factors such as wind speed and surface texture, the surface area (A) exposed to the fluid, and the temperature difference (ΔT) between the surface and the surrounding fluid. It is governed by the following equation:

$$\text{Rate of heat convection, } Q_{\text{conv}} = Ah(\Delta T)$$

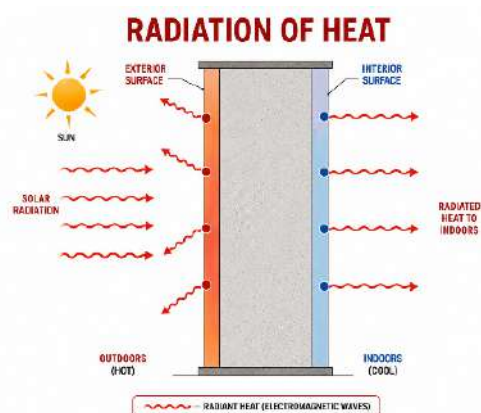


Convection can occur due to natural air movement driven by temperature-induced density differences (e.g., hot air rising near a sun-exposed wall), known as natural convection, or due to external forces such as wind or mechanical ventilation, known as forced convection. Surfaces exposed to higher wind speeds or mechanical air movement (such as exposed rooftops or building facades along open streets) lose or gain heat more rapidly through convection than sheltered surfaces (such as walls shaded by adjacent buildings or vegetation), which experience comparatively slower convective heat exchange.

Radiation refers to the transfer of heat through electromagnetic waves and does not require a physical medium. Heat is exchanged between warmer and cooler surfaces through radiation.

Solar radiation striking a building's roof and walls is absorbed by the building envelope, and part of this radiant heat is also re-emitted into the indoor space, raising the building's indoor temperature. This is an example of how radiation contributes to heat ingress in buildings.

Heat transfer through radiation depends on the surface emissivity (ϵ), the Stefan-Boltzmann constant (σ), the surface area (A) and the difference between the fourth powers of the absolute temperatures (T) of the radiating surfaces. It is governed by the following equation:



$$\text{Rate of heat radiation, } Q_{\text{rad}} = \epsilon \sigma A (T_1^4 - T_2^4)$$

Dark-coloured building surfaces, such as dark-coloured roofing sheets or unpainted concrete, have high solar absorptance and readily absorb and re-radiate solar heat, resulting in significantly higher indoor temperatures. On the other hand, lighter-coloured surfaces, such as cool-roof coatings, have high solar reflectance and reflect a significant portion of incoming solar radiation, reducing heat absorption, and keeping indoor spaces relatively cooler.

Thermal Mass and Specific Heat Capacity: Thermal mass refers to a material's capacity to absorb, store, and later release heat. It depends on the material's specific heat capacity, which is the amount of energy required to raise the temperature of a unit mass of the material by 1°C, as well as its density and volume. A material with high thermal mass, such as concrete, stone, or brick, absorbs heat slowly over the course of the day and releases it slowly at night, acting as a thermal buffer that delays and reduces indoor temperature fluctuations relative to outdoor conditions.



The usefulness of thermal mass depends on the diurnal temperature range, the difference between the daytime high and night-time low, at a given location. Where this difference is large, as in Hot-Dry climates, thermal mass has a cool night to discharge its stored heat into, keeping average indoor temperatures below the outdoor peak. Where the difference is small, as in Warm-Humid climates, thermal mass has no cool period to release into, so it instead keeps accumulating heat day after day, working against indoor comfort rather than for it. This is why the effectiveness of high-thermal-mass materials depends on the climate zone in which they are used rather than being an inherent property of the material.

Thermal Transmittance (U-Value) and Thermal Resistance (R-Value): Thermal transmittance (U-value) and thermal resistance (R-value) describe how readily heat passes through a building material or an assembly of materials that constitute a building feature. R-value measures the thermal resistance, the ability of a material to effectively resist conductive heat flow, expressed in $\text{m}^2\text{K/W}$. A higher R-value denotes that the material is a better insulator. U-value measures the thermal transmittance, expressed in $\text{W/m}^2\text{K}$, and is mathematically the reciprocal of R-value ($U = 1/R$). A lower U-value means less heat is conducted through the material for a given temperature difference. Building codes such as the Eco-Niwas Samhita (ENS) specify the thermal performance requirements for building materials such as insulation products using these values.

For example, the R-value of a multi-layer wall assembly with plaster, brick, and insulation layers is calculated by adding the R-values of each individual layer. The assembly's total R-value is then inverted to arrive at the overall U-value. This is why an assembly's real-world thermal performance depends on the combined performance of all its layers, and why building codes and standards set a minimum performance requirement for an assembly as a whole rather than for any single building material in isolation.

Basics of Psychrometry: Psychrometry is the study of the properties of moist air, the mixture of dry air and water vapour that makes up the atmosphere, and explains why the same cooling strategy performs differently in different climates. The four key properties are explained briefly below:

Relative Humidity (RH) is the amount of water vapour in the air, expressed as a percentage of the maximum amount the air could hold at that temperature before becoming saturated.

Dew Point Temperature is the temperature at which air becomes fully saturated (100% RH), and water vapour begins to condense, the reason a cold glass of water "sweats" in humid weather.

Wet-bulb Temperature is the lowest temperature to which air can be cooled by the evaporation of water at constant pressure. It is always at or below the dry-bulb air temperature, and the two converge as the air approaches saturation.

Humidity Ratio (specific humidity) is the actual mass of water vapour present per unit mass of dry air, independent of temperature, unlike relative humidity.

These properties determine why some cooling strategies work only in specific climate zones. For example, evaporative cooling is effective in Hot-Dry climates as it works by using heat from the air to evaporate water, which is only possible when the air's relative humidity is well below saturation levels. The drop in dry-bulb temperature achievable through evaporation is directly related to the gap between the dry-



bulb and wet-bulb temperatures, known as the wet-bulb depression. In a Hot-Dry climate, this gap is large, so evaporative cooling can achieve a substantial temperature drop. In a Warm-Humid climate, the air is already close to its wet-bulb temperature, so the gap is small, and evaporative cooling has very little cooling capacity left to deliver. This explains why the technique works well in a Hot-Dry region but performs poorly in a Warm-Humid region such as Kerala.

What is Thermal Comfort?

Thermal comfort is the condition of mind that expresses satisfaction with the surrounding thermal environment and is assessed subjectively by occupants rather than measured directly by a single instrument. It depends on four environmental factors: air temperature, radiant temperature, air speed, and humidity. It is also influenced by two personal factors: the body's metabolic rate, which depends on activity level, and clothing insulation. This is why **thermal comfort is expressed as a range of acceptable conditions rather than one fixed ideal temperature. The same air temperature can feel comfortable or uncomfortable depending on humidity, air movement, and what a person is doing and wearing.**

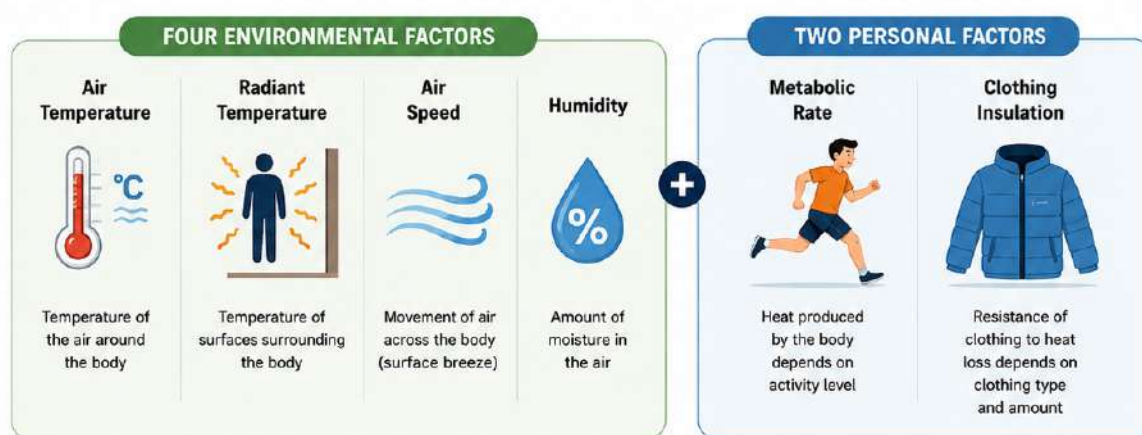


Figure 2: Factors Affecting Thermal Comfort Level

What is the Urban Heat Island (UHI) Effect?

The Urban Heat Island (UHI) effect describes the phenomenon in which dense urban areas record significantly higher daytime and night-time temperatures than their surrounding rural or less-developed peripheries, sometimes by several degrees Celsius. While **conduction, convection, and radiation** describe heat transfer at the scale of a single building material or surface, the **UHI effect describes their combined influence on an entire city's surfaces and materials.**

UHI arises from several factors such as heat-retaining building materials that re-radiate heat well into the night, reduced green and blue cover that lowers the natural cooling effect from evapotranspiration and shading, and the reduced natural ventilation caused by dense urban development. Waste heat rejected from vehicles, air conditioners, and industrial processes adds a further, direct heat source compared to a city's peripheral and surrounding rural areas. The **UHI effect is best understood as the aggregate outcome of many individual building design decisions rather than as a separate physical phenomenon.**



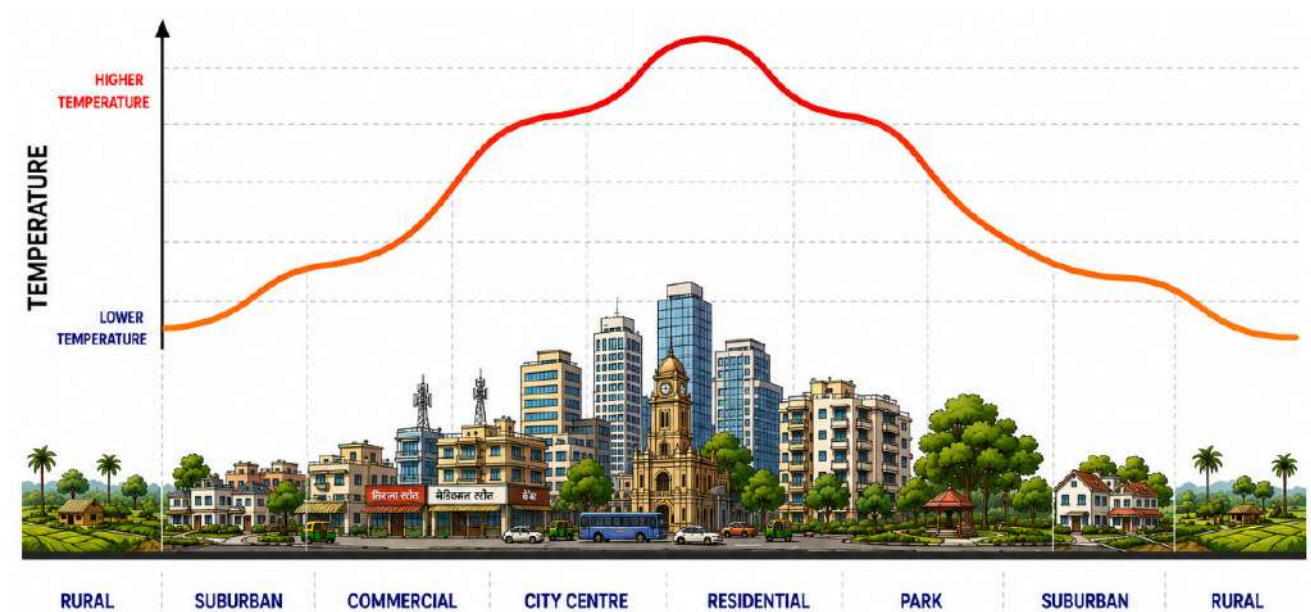


Figure 3: Illustration of UHI effect across city transects [Adapted from U.S. EPA (2008)²]

² U.S. Environmental Protection Agency. (2008). Reducing Urban Heat Islands: Compendium of Strategies. <https://www.epa.gov/heat-islands/heat-island-compendium>



02 Climate Change and Urban Built Environment

2.1 | Urbanisation and Extreme Heat Impacts

India's annual mean temperature increased by 0.15°C per decade between 1951 and 2016, making extreme heat a critical climate risk,³ with far-reaching impacts on health, employment, infrastructure, and economic productivity. Reduced labour productivity due to extreme heat could lead to a loss of 35 million jobs,⁴ amounting to 4.5% of GDP by 2030.⁵ With more than 40% of India's population projected to live in urban areas by 2030, there is an urgent need to prioritise heat-resilient urban planning.

Rapid urbanisation, combined with climate change, has been intensifying heat exposure in cities, threatening infrastructure, public health, and livelihoods. A study of India's eight largest metropolitan cities reported an average 98% increase in built-up area (total land area covered by buildings in a city) between 1995 and 2025.⁶ Higher built-up areas increase heat absorption, mainly due to the use of materials such as concrete and asphalt, which have low albedo and high thermal conductivity, resulting in higher air temperatures in urban areas than in surrounding non-urban areas, commonly known as the UHI effect.

A study across 141 cities in India, which separated the impacts of urbanisation and climate on heat, found that urbanisation alone accounted for 40% of urban warming, leading to a temperature increase of $0.2 \pm 0.15^\circ\text{C}$ per decade. This contribution was as high as 70–100% in Tier 2 cities, which are undergoing rapid urbanisation and economic growth.⁷ Moreover, vulnerable urban population groups such as the elderly, children, people with disabilities, people with chronic illnesses, low-income settlements, outdoor workers and pregnant women remain disproportionately affected by extreme heat.

2.2 | Building Design Factors Affecting Heat Resilience

The design of built infrastructure strongly influences heat risk exposure and thermal comfort. For example, low-income settlements face higher heat risks due to poorly insulated roofs made of materials such as asbestos and tin, lack of cross-ventilation, closely clustered housing, limited shading, and minimal green cover. Heat resilience in buildings refers to their ability to maintain comfortable and safe indoor temperatures despite rising external heat. This can depend on several factors, described below.

Building form and orientation: Building form refers to the shape or configuration of a building, including its size, height, volume, and layout. It determines how much space must be heated or cooled and how wind will flow around it when put together in a layout. Orientation refers to the position of a building relative to the sun's path and prevailing wind direction. This affects solar radiation penetration at

3 Council on Energy, Environment and Water (2025). How Extreme Heat is Impacting India: Assessing District-level Heat Risk. <https://www.ceew.in/sites/default/files/mapping-climate-risks-and-impacts-of-extreme-heatwave-disaster-in-indian-districts.pdf>

4 International Labour Organisation. (2019). Working on a Warmer Planet: The Impact of Heat Stress on Labour Productivity and Decent Work. https://www.ilo.org/sites/default/files/wcmsp5/groups/public/@dgreports/@dcomm/@publ/documents/publication/wcms_711919.pdf

5 Woetzel et al. (2020). Climate Risk and Response: Physical Hazards and Socioeconomic Impacts. McKinsey & Company

6 Square Yards (2025). Cities in Motion - Tracing 30 Years of Urban Expansion in Key Indian Cities. https://static.squareyards.com/Cities_in_Motion-Tracing_30_Years_of_Urban_Expansion_in_Key_Indian_Cities-SquareYards_Final.pdf

7 Sethi, S. S., & Vinoy, V. (2024). Urbanization and regional climate: The linked warming of Indian cities. <https://doi.org/10.1038/s44284-024-00074-0>



different times of day and across seasons, and the airflow entering buildings.

Building envelope: The building envelope is the physical barrier separating the building interior from the outdoor environment and includes walls, roofs, windows, and doors. It plays a key role in regulating indoor temperatures and heat. Factors such as window glazing, roof reflectivity, and the thermal conductivity of wall materials influence a building's heat resilience.

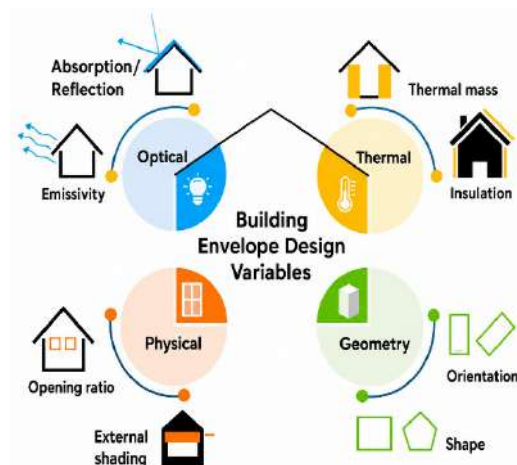


Figure 4: Building Envelope Design Variables [Source: Gupta et al. (2023)⁸]

Building materials play a key role in temperature regulation. Materials with higher thermal mass readily absorb and store heat during the day, acting as heat sinks, before releasing it slowly at night. High-density materials such as concrete, brick, and stone have high thermal mass, while materials such as wood, hollow clay, aerated concrete, and plastics have lower thermal mass.

Shading reduces the amount of solar radiation entering a building and can reduce cooling loads by 15–20% during peak hours.⁹ Shading can be internal (curtains, louvered shutters, blinds) or external (overhangs, vertical devices such as fins, louver blades, and egg-crate shading devices). Shading can also be enhanced through vegetation and greening.

Ventilation: Natural and mechanical ventilation strategies improve thermal comfort by allowing indoor air to circulate through openings such as windows, doors, chimneys, and ventilators, as well as mechanical components like valves. The number and placement of openings relative to prevailing wind direction play a key role in improving ventilation and heat resilience.

Microclimate: The surrounding microclimate of a building plays an important role in regulating temperature and heat risk for building occupants. Nearby water bodies and vegetation influence neighbourhood-scale temperature regulation. Studies show that greenery near buildings can reduce peak surface temperatures by 2–9°C.¹⁰ The following section explores how different elements of the urban built environment influence the microclimate which in turn affects the heat resilience of buildings.

8 Gupta et al. (2023). Envelope design for low-energy buildings in the tropics: A review. <https://doi.org/10.1016/j.rser.2023.113650>

9 Xiao, X., et al. (2025). Shading effects on building energy performance: A multi-city analysis. Results in Engineering. Advance online publication. <https://doi.org/10.1016/j.rineng.2025.106870>.

10 Wong et al. (2021). Greenery as a mitigation and adaptation strategy to urban heat. <https://doi.org/10.1038/s43017-020-00129-5>.



2.3 | Urban Planning for Heat Resilient Built Environment

Building design factors such as envelope design, orientation, shading, and material selection determine how heat is gained, stored, transferred, and dissipated within a building. However, **the surrounding urban environment sets the baseline conditions that buildings must contend with to act as a buffer against outdoor heat and maintain comfortable indoor temperatures.** Two identical buildings can experience significantly different thermal loads depending on street geometry, surface composition, and vegetation cover in their immediate surroundings. Urban planning can improve heat resilience at a larger scale by shaping the surrounding microclimate, often achieving more than any envelope-level intervention alone. The key urban-scale factors that interact directly with the building design factors discussed in Section 2.2 are explained below.

Urban Canyon Geometry and Sky View Factor: The width-to-height ratio of streets, called the “urban canyon”, determines how much solar radiation reaches ground level through gaps between buildings and how heat becomes trapped through multiple reflections between building façades. The sky view factor determines how effectively long-wave radiation escapes to the sky at night. A low sky view factor, typical of narrow streets flanked by tall buildings, traps re-radiated heat and slows nighttime cooling, a major contributor to elevated night-time temperatures in dense South Asian cities in hot climate zones. Conversely, wider streets without adequate shading maximise direct solar exposure during the day.

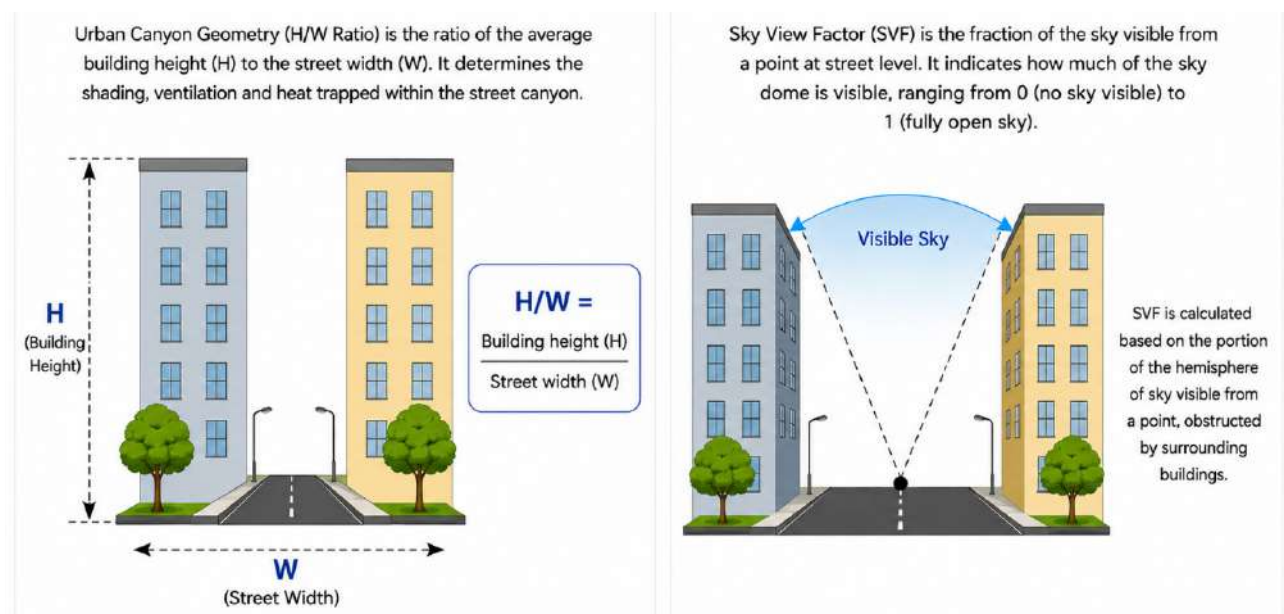


Figure 5: Urban canyon geometry (H/W ratio) and sky view factor [Adapted from Oke, T.R. (1981)¹¹]

Local or state urban planning guidelines should provide guidance on street planning and building design by calibrating street-width-to-building-height ratios and aligning buildings and streets with prevailing wind directions and solar paths to balance daytime shading with nighttime cooling driven by wind flow.

Land Surface Composition: Impervious urban surfaces such as asphalt roads, concrete pavements, and dark roofs have low albedo (high solar absorptance) and high thermal mass. As a result, 80–95% of incident solar radiation is absorbed rather than reflected, converted into sensible heat, stored during

¹¹ Oke, T. R. (1981). Canyon geometry and the nocturnal urban heat island: Comparison of scale model and field observations. *Journal of Climatology*. <https://doi.org/10.1002/joc.3370010304>



the day, and gradually released after sunset. This process drives the UHI effect, in which densely developed city centres experience air temperatures several degrees higher than surrounding peripheral or rural areas.

The same impervious surfaces also prevent rainwater from percolating through soil layers and recharging groundwater. Covering the ground with asphalt or concrete reduces rainwater infiltration into the soil, lowering soil moisture. This, in turn, reduces the evaporative cooling that moist soil and vegetation would otherwise provide, reinforcing the UHI effect. Lower soil moisture in built-up areas leads to dry, impervious urban surfaces that can reach very high temperatures, further increasing ambient air temperatures.

Therefore, lighter-coloured or open-graded permeable surfaces typically have lower thermal mass and higher albedo than conventional asphalt, reducing daytime heat absorption and nighttime re-radiation. The retained soil moisture can support evapotranspiration,¹² providing a passive cooling effect that a purely reflective yet sealed surface cannot offer.

Urban planning guidelines should specify the use of high-albedo or permeable paving in public infrastructure or rights-of-way, limit the extent of continuous dark impervious cover in new developments, establish plot-level surface specifications, and incorporate material properties such as high reflectance and high emissivity in urban planning and building design guidelines.

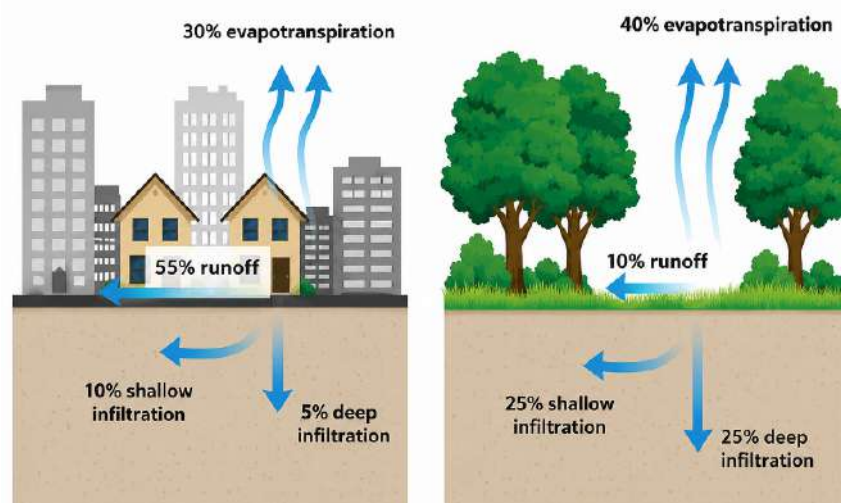


Figure 6: Impervious surfaces and reduced evapotranspiration [Source: U.S. EPA (2008)¹³]

Green-Blue Infrastructure as Microclimate Regulators: Vegetation, especially tree cover, and water bodies can significantly cool their surroundings primarily through evapotranspiration and shading rather than reflectivity alone. This makes tree canopy cover, green corridors, and water bodies functionally distinct from cool-roof or reflective-surface strategies at the building scale, enabling them to greatly reduce heat stress over a much wider area.

Development in urban areas should be planned with a contiguous network of street trees, urban parks,

¹² Evapotranspiration describes the transfer of latent heat, what we feel as humidity, from the Earth's surface to the air via evaporating water.

¹³ U.S. Environmental Protection Agency. (2008). Reducing Urban Heat Islands: Compendium of Strategies. <https://www.epa.gov/heat-islands/heat-island-compendium>



and water features to lower the ambient air temperature over a wider radius than isolated green patches. This reduces the radiant heat load on building façades. Green cover should be developed as connected infrastructure that is carefully sized, spaced, and designed with species selection to enhance canopy density in public and residual open spaces in densely developed areas where building-level retrofit options are constrained.

Density, layout, and airflow in the built environment: Building layout and density within a specific area influence natural ventilation by obstructing or channelling prevailing winds. Compact, staggered, and high-density development without adequate spacing can create wind shadows that trap heat and pollutants at the street level, undermining the effectiveness of individual passive building cooling strategies. Layout planning should account for prevailing wind direction by using staggered building placement, ventilation corridors, and strategically varied building heights and density rather than allowing uniformly dense development. This allows prevailing winds to move freely through such areas, maintaining airflow that helps buildings relying solely on natural cross-ventilation for indoor comfort.

Anthropogenic Heat Sources: Waste heat from vehicles, air-conditioning condensers, and industrial activity adds directly to the ambient thermal load around building façades. As outdoor temperatures rise, cooling demand increases, resulting in more waste heat being rejected into the already warm surroundings. Urban cooling interventions such as green spaces can help moderate these impacts when prioritised through area-level planning that accounts for the distribution of anthropogenic heat sources in the city.

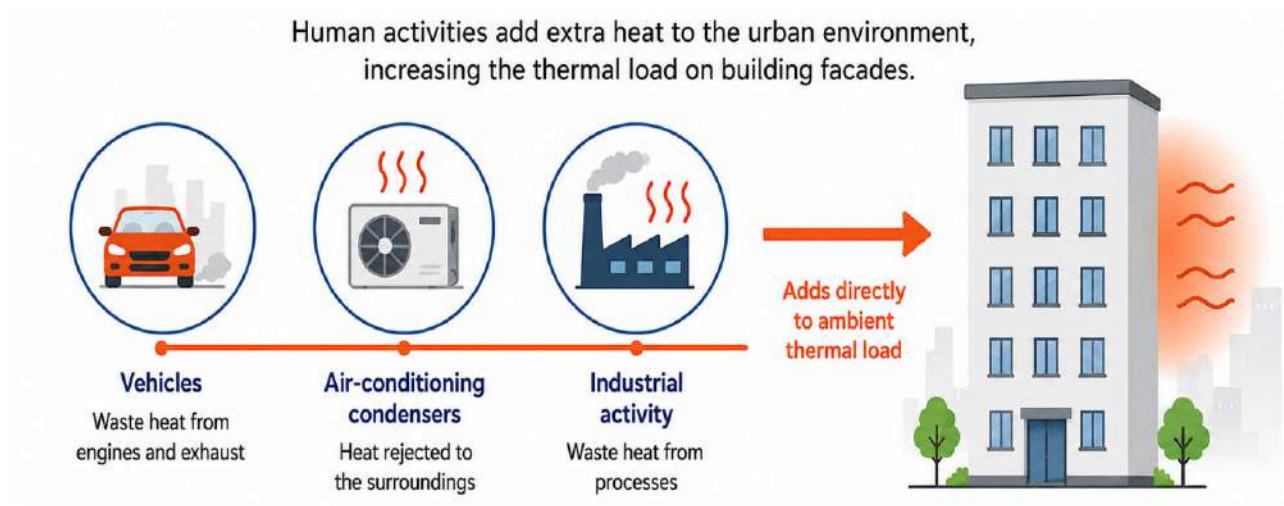


Figure 7: Anthropogenic heat sources at neighbourhood-scale impacting building thermal load

A well-designed building with passive cooling features can still experience elevated ambient temperatures in a narrow and poorly ventilated street with low-albedo surfaces. This erodes the thermal benefits of its envelope design. Conversely, a favourable urban-form sky view factor, high-albedo surfaces, green cover in the vicinity, and unobstructed airflow improve the effectiveness of building-level heat resilience interventions. **Heat-resilience consideration in building design and urban planning should therefore be treated as complementary strategies within an adaptation approach for improving heat resilience of urban built environment.**



03 Heat Resilience Strategies for Buildings

In the Indian climate context, maintaining indoor temperatures between 25°C to 30°C through natural ventilation is generally considered thermally comfortable.¹⁴ Thermal comfort requirements vary significantly depending on building typology, occupancy levels, and the climatic zone in which the building is located. For example, commercial buildings in hot-climate regions should minimise glass façades to limit solar heat gain, while in colder regions they may adopt higher glazing ratios to maximise daylighting and passive heating. Building material selection and cooling strategies should therefore always align with the region's macroclimatic characteristics.

During the design of buildings, a passive strategy can help maintain thermal comfort in one climate zone but may be counterproductive in another. Climate zone determines which combination of strategies can actually cool a building. Therefore, the climate characteristics of the building site should be understood before selecting specific passive cooling measures or building materials.

As per the National Building Code (NBC), 2016, India is divided into five climatic zones for building design: Hot-Dry, Warm-Humid, Temperate, Cold, and Composite. This guidebook focuses on the Hot-Dry, Warm-Humid, and Composite climatic zones, which together cover more than 75% of India's land area and accommodate the majority of its urban population. Cold and Temperate/Moderate zones (e.g., the Himalayan region and parts of the Western Ghats) prioritise heat retention over heat rejection and are not addressed here. Please refer to NBC 2016, Energy Conservation Building Code (ECBC) 2017 and other such codes for zone-specific guidance.

Hot-Dry: This climate zone is characterised by large diurnal (day-night) temperature swings and low humidity. Materials with high thermal mass, courtyard-style architecture, and evaporative cooling work well since heat absorbed by day can be released at night.

Warm-Humid: This type of climate is characterised by small diurnal temperature swings and high humidity. Thermal mass and evaporative cooling are less effective as there is little nighttime cooling to dissipate indoor heat, while high humidity limits evaporation. Lightweight construction based on low-thermal mass materials and continuous cross-ventilation are more effective.

Composite: This climatic zone witnesses hot summers and cold winters and therefore requires passive cooling strategies and material choices that perform well across seasons. Materials with moderate thermal mass and insulation properties are generally suitable, while shading strategies should be adjustable based on the season.

The passive cooling strategies and building material options presented in the following sections should be considered based on the city's climate zone and geographic location, as latitude and longitude determine the solar angles.

¹⁴ Bureau of Indian Standards. (2016). National Building Code of India 2016.



3.1 | Passive Cooling Strategies

Passive cooling strategies use natural energy sources such as sunlight and wind, together with material properties such as thermal mass to maintain comfortable indoor temperatures while reducing reliance on mechanical cooling systems such as air conditioners. Passive cooling strategies enhance a building's heat resilience by reducing indoor heat gain, lowering energy demand, and improving the thermal comfort of the building occupants.

Passive cooling strategies fall into three categories: microclimate level, building envelope and natural ventilation. Microclimate level strategies include building form, orientation, and landscape strategies that control heat gain and reduce UHI. Building envelope design factors such as window-to-wall ratio (WWR), thermal transmittance (U-value), thermal mass of materials and strategies such as shading, insulation, glazing, and cool roofs, together regulate how much heat the building absorbs. Natural ventilation strategies use airflow and thermal buoyancy to cool spaces directly and dissipate excess indoor heat.

Wall and roof material selection is covered in more detail, including thermal characteristics and costs for comparisons, in the Building Material Options section (**Section 3.2**) of this guidebook. The strategies presented below focus on the underlying design logic such as matching thermal mass to climate and adding insulation layers rather than suggesting specific material choices.

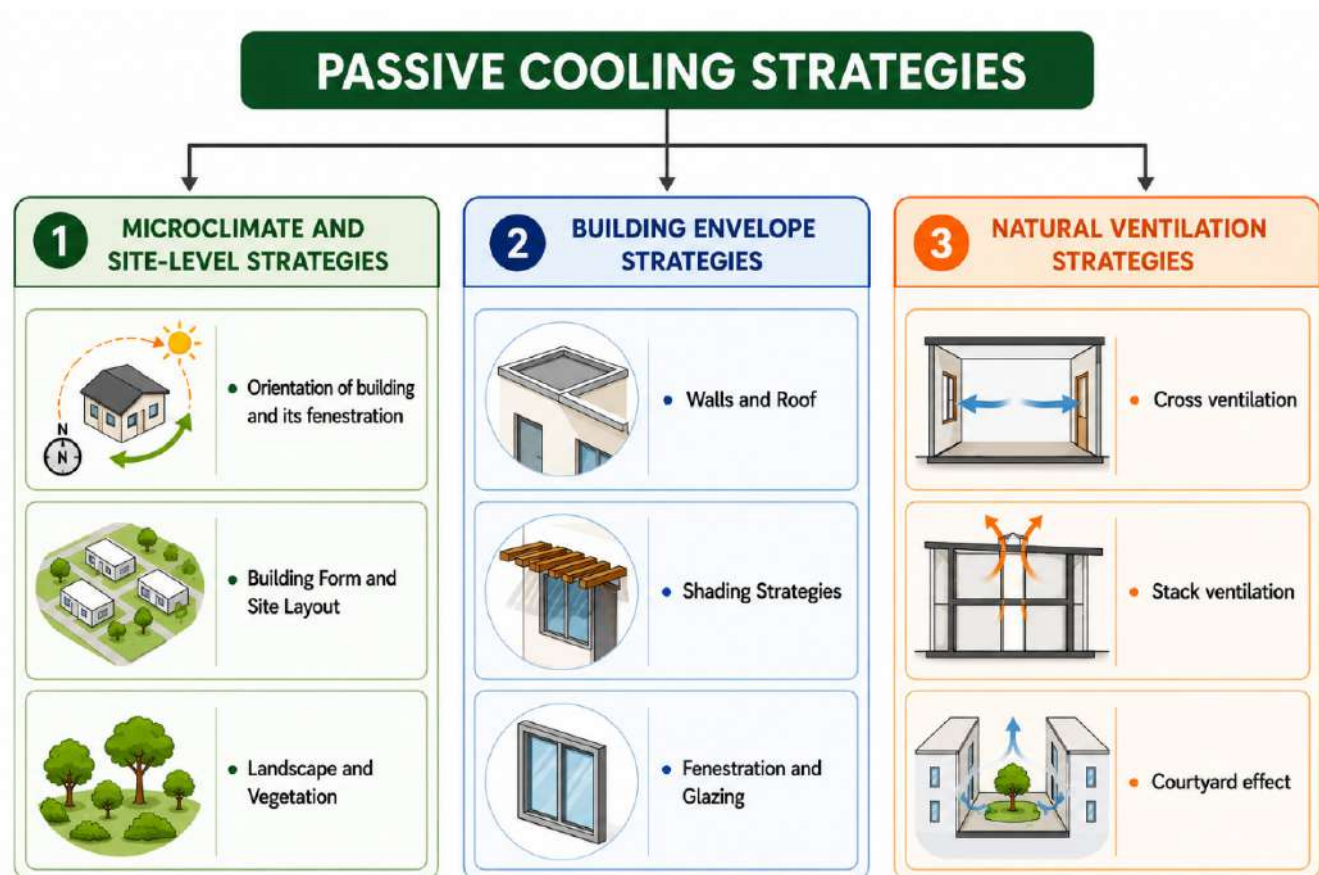


Figure 8: Passive cooling design strategies



3.1.1 Microclimate and Site-Level Strategies

Orientation of building and its fenestration: Orient the building's longer facades along the north-south axis to minimise east-west solar exposure, which is the most difficult orientation to shade effectively, using building envelope features such as overhangs and recessed windows. ***Buildings with longer north-facing facades and window openings get more indirect daylight with minimum heat gain.***

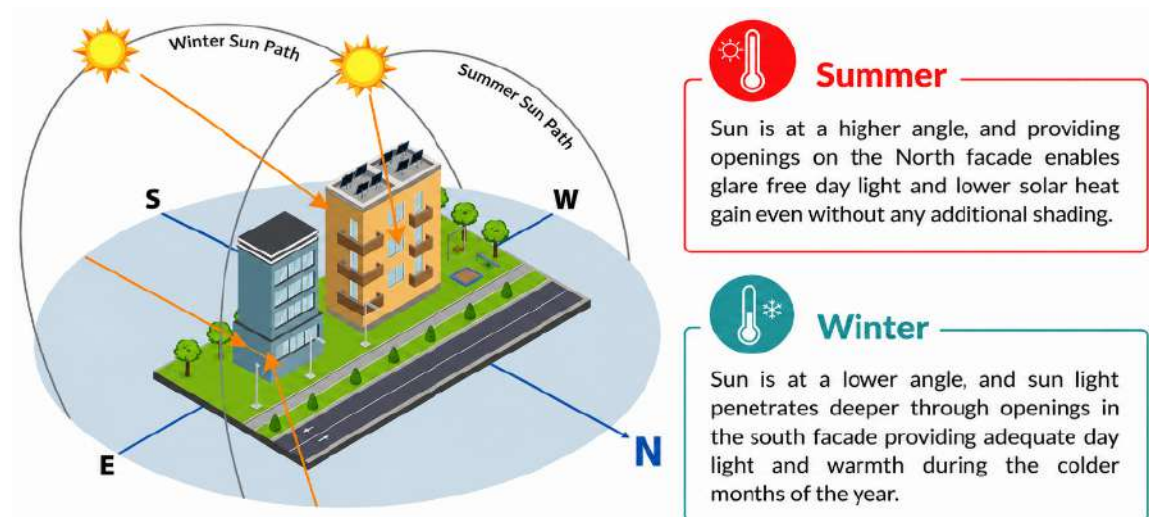


Figure 9: Illustration for North-South Orientation of Buildings

Keep building fenestrations such as window openings and doors on east- and west-facing facades to a minimum, as they are usually the weakest parts of a building's thermal envelope. If fenestrations on east- and west-facing walls are unavoidable, provide deep vertical fins or overhangs to shade them, especially during the sunrise and sunset hours. North- and south-facing facades receive more manageable, lower-angle sunlight and are easier to shade using horizontal devices.

Align the building's longer axis roughly perpendicular to prevailing summer winds (within 0°-30°) to maximise cross-ventilation potential. Where solar orientation and wind direction conflict, prioritise solar orientation and use wing walls or vegetation to redirect airflow.

Building Form and Site Layout: Design compact building forms with a lower surface-to-volume ratio, (for example, square footprints) to reduce heat gain, but this may also limit daylight access. Elongated building forms improve daylighting but increase the exposed surface area. The building design should balance the two based on climate context.

In building clusters, arrange buildings in ascending height and staggered layouts rather than creating a continuous wall of buildings. This allows airflow to reach lower floors and internal buildings instead of being blocked at the windward edges of the buildings.





Figure 10: Illustration of staggered placement of buildings with varying form to enable airflow

Design buffer zones such as staircases, storage rooms, corridors, and bathrooms on the east-west sides to shield habitable spaces from direct heat gain. Placing habitable rooms along the north-south facing sides to make it easier for shading design.

Landscape and Vegetation: Vegetation is one of the most cost-effective microclimate strategies available. Plant trees and shrubs closer to buildings to shade building surfaces and paved areas, while cooling the surrounding air through evapotranspiration. Species and placement choices matter as much as the presence of vegetation itself. Plant deciduous trees on south-facing sides in composite climates as they shade the building in summer and allow sunlight penetration once the leaves drop in winter. Prioritise native species of trees and shrubs with low water requirements, as they can grow with minimal irrigation and care, and would already be suited to the local temperature and rainfall patterns.

Minimise hard paving and replace it with permeable paving or grass pavers. Vegetated pergolas can also provide shading. These measures reduce surface heat gain and retention, and mitigate the local UHI effect.

3.1.2 Building Envelope Strategies

Wall and Roof Design: During the design stage, select the building wall and roof assemblies, including materials, coatings, and cavities, based on the overall U-value (thermal transmittance) across the surface of the assemblies. Lower U-values reduce the heat conducted through the building envelope, limiting indoor heat gain.

Match the thermal mass of walls and roofs to the climatic zone where the building is located. High thermal mass materials such as concrete, stone, and brick masonry are effective in regions with Hot-Dry climate that has high diurnal temperature swings. In Warm-Humid climates, where there is minimal diurnal variation, high thermal mass can trap heat instead of releasing it. Lightweight and low thermal mass construction performs better in these cases.

Where possible, place insulation on the outer, warmer side of the building envelope. This reduces the rate of heat transfer into the thermal mass instead of just slowing its release indoors. Opting for low-cost strategies such as cool roofs with high solar reflectance and thermal emittance, expressed as the Solar Reflectance Index (SRI), can help reduce roof surface



temperatures.

Using light-coloured or reflective coatings for walls can lower indoor temperatures by several degrees at minimal or no added cost over conventional surface coatings both for walls and roofs. **The roof is typically the most solar-exposed envelope element, and it is recommended to invest in insulation or low-cost reflectivity enhancement options such as 'Cool Roofs' where roof insulation is not feasible due to structural or budget constraints.** Cool roof coatings work by increasing the roof surface's solar reflectance and thermal emittance, together expressed as the Solar Reflectance Index (SRI), so that less solar heat is absorbed by the building envelope and conducted indoors.

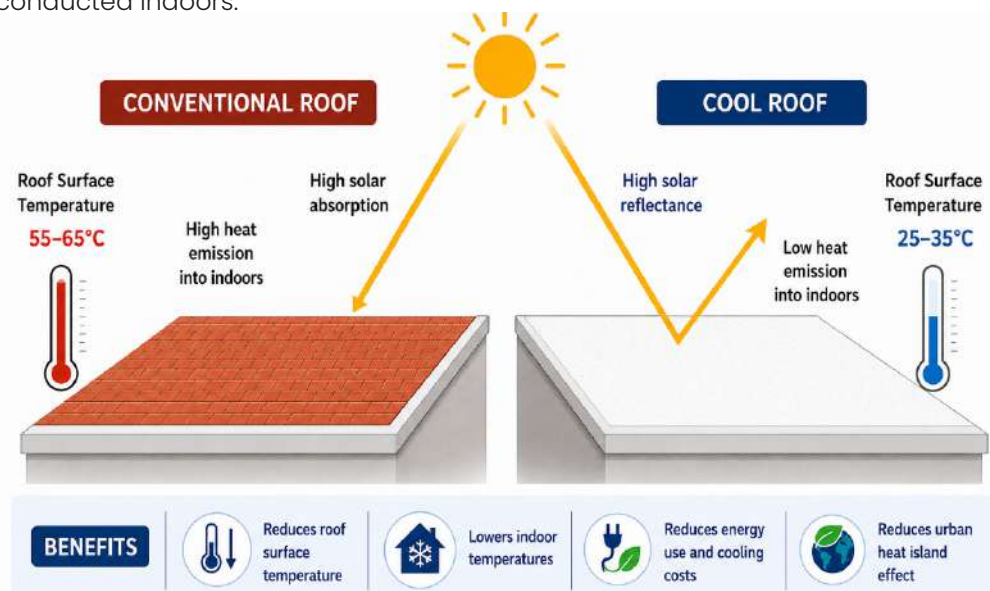
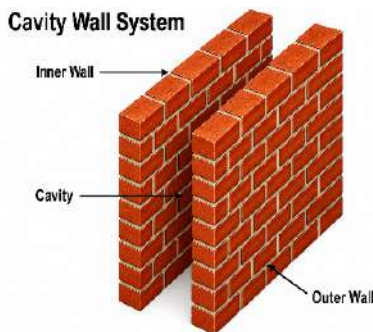


Figure 11: Cool roof concept and its benefits



Alternative construction techniques such as cavity walls (brick-airgap-brick) and rat-trap bond masonry delay heat transfer through an internal air gap without needing additional insulation material. Such construction techniques have higher initial cost and may need specialized labour but are cost-effective over the building's lifecycle since they reduce cooling energy demand without relying on manufactured insulation products.

Where feasible, install green roofs and vertical gardens that provide thermal insulation through vegetation while reducing solar heat gain from walls and roofs. Creepers and climbers growing on trellises provide flexible, low-cost shading for verandahs and walls. Green roof and vertical greening strategies work by adding thermal resistance to heat conduction, while also cooling the surrounding air through evapotranspiration. These strategies are explained further in **Chapter 4.**

Shading Strategies: Opting for external shading devices is always more effective than internal shading devices because internal shading devices such as blinds and curtains absorb heat after it has entered the building.



As discussed under building orientation strategies, north-facing openings need minimal shading in most climate zones, mainly to block high-angle summer sun. South-facing openings generally need deep horizontal overhangs as they receive direct sunlight for much of the year, although the solar angle varies with geographic location. **East- and west-facing openings are the hardest to shade, since they receive direct low-angle sunlight, especially during the hours after sunrise and before sunset. The overall window area on these facades should be minimised, and vertical fins or louvers should be prioritised over horizontal overhangs.**

Shading device sizing is guided by the projection factor, the ratio of the shading device depth to window height or sill height, and by horizontal and vertical shadow angles, which describe the sun's position relative to the façade. Deeper overhangs or fins are required for buildings where the solar angles are lower relative to the facade. When a single deep overhang or vertical fin is impractical, it can be divided into multiple smaller overhangs or fins at different levels to achieve an equivalent shading effect. These can also serve as light shelves that reflect daylight deeper into the room. Fixed external overhangs fixed during the initial design stage typically cost no more than a conventional chajja, while fabricated louvers, fins, and retractable awnings have higher upfront costs but can offset these through reduced cooling load over the building's life.

Self-shading features can also be built into the building's own form rather by using separate shading devices. This is done by integrating balconies, inclined walls, and other architectural projections into the building design that can shade not only window openings but also walls and roof surfaces around them, reducing the solar heat gain across the envelope rather than at the openings alone. Since this shading comes from the building's mass itself, it needs to be considered at the early-design stage, alongside overall form and orientation, and is generally unsuitable for retrofitting existing buildings.

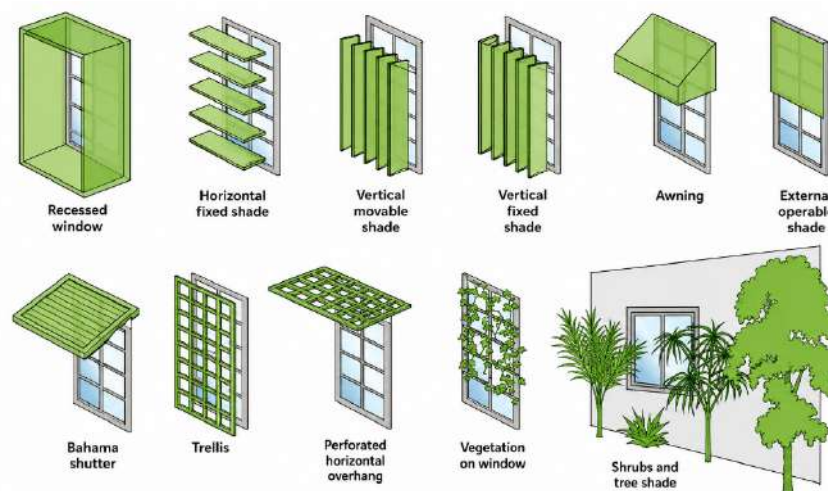


Figure 12: Illustration of Shading Strategies [Source: Al-Yasiri et al. (2021)¹⁵]

Fenestration and Glazing: Determine the Window-to-Wall Ratio (WWR), defined as the ratio of vertical fenestration area to gross exterior wall area, according to the local climate zone while designing windows for a building. **A higher WWR increases daylight availability but also increases solar heat gain unless combined with shading devices or high-performance glazing.**

¹⁵ Al-Yasiri, Q., & Szabó, M. (2021). A short review on passive strategies applied to minimise the building cooling loads in hot locations. <https://doi.org/10.14232/analecta.2021.2.20-30>.



Prioritise glazing with a low U-value and a low SHGC.¹⁶ Together, these factors, defined together as Relative Heat Gain (RHG)¹⁷, determine the total heat gain through glazing. It is recommended to choose glazing with low relative heat gain in hot climates, while still opting for higher visible light transmittance (VLT)¹⁸ where possible, so that heat gain is minimised without increasing dependence on artificial lighting, which would only add to the internal heat load.

Use insulated glazing units, double or triple glazing, or low-emissivity (Low-E) coatings to cut solar heat gain while maintaining visible light transmission. These measures can directly control the heat entering through glazed surfaces without sacrificing daylight.

Choose window or door frame materials with thermal breaks, such as insulated metal, wood, or vinyl, to avoid thermal bridging, particularly in actively cooled buildings. Also, it is important to seal window-to-frame and frame-to-wall junctions with weatherstripping and caulking to prevent uncontrolled air leakage, or infiltration, which can impact heat ingress into buildings.

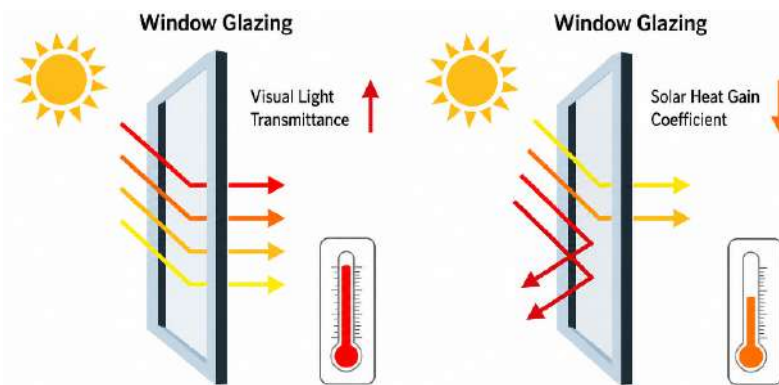


Figure 13: Window glazing performance metrics

Daylighting strategies can also improve heat resilience indirectly by reducing reliance on artificial lighting. **Daylighting strategies such as use of light-coloured or reflective interior paints and light shelves allow adequate daylight with smaller glazing areas, indirectly keeping the WWR, and solar heat gain, lower.** Traditional Indian 'Jaali' is an excellent example for passive design of buildings to achieve optimal day lighting, while also aiding free airflow through the interior spaces of buildings.

Similar principles apply to design of skylights, roof monitors, and tubular skylights such as solar tubes, which can be used to illuminate poorly lit indoor spaces, especially ones that receive little day lighting from sun. Design these with reflective surfaces and account for seasonal solar angles to avoid glare and unwanted heat gain. The skylights should also be oriented towards the north, where possible, since this admits more consistent daylight with lower solar heat gain.

3.1.3 Natural Ventilation Strategies

Cross ventilation: This is a wind-driven ventilation mechanism that relies on openings on

¹⁶ Solar Heat Gain Coefficient is the fraction of solar radiation striking a window or glazed surface that actually ends up as heat inside the building, counting both the sunlight that passes straight through and the portion the glass absorbs and then re-radiates inward.

¹⁷ Relative heat gain refers to the total amount of heat that passes through a glass pane, considering both the solar heat gain (measured by the SHGC) and the conductive heat gain (measured by the U-value).

¹⁸ Visible Light Transmittance is the fraction of visible light, the portion of sunlight the human eye can see, that passes through a glazing material, expressed as a value between 0 and 1 or as percentage.



opposite or adjacent facades to let the wind pressure drive airflow through the building, from the higher-pressure windward side to the lower-pressure leeward side. Cross ventilation is one of the most reliable and cost-effective technique for improving natural ventilation in buildings. Figure 14 illustrates the dos and don'ts for design of cross ventilation openings.

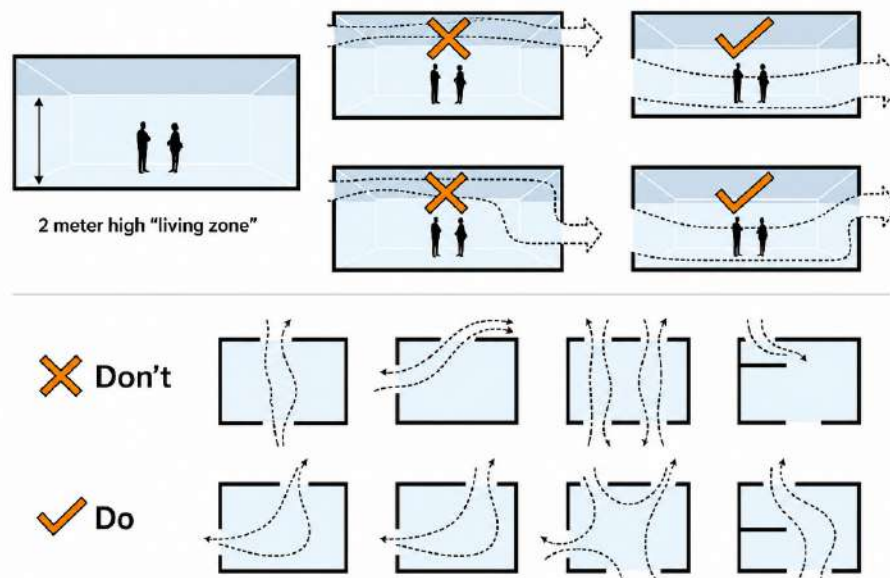


Figure 14 Dos and Don'ts for placement of cross ventilation openings

Stack ventilation: This is a buoyancy-driven ventilation strategy that relies on the temperature difference between indoor and outdoor air. As warm indoor air rises and exits through high-level openings (through stacks or high-level roof openings), the negative pressure near floor level draws in cooler air through low-level openings. This works best when stacks or wind towers are integrated into the building design with a meaningful height difference between inlet and outlet openings.

Stacks or wind towers are tall vertical shafts, often glazed at the top, that allow warm air to rise and escape through high-level openings, while cooler air is pulled in through low-level openings. This is particularly **effective in tall or multi-storied buildings that have vertical shafts opening to the sky or service shafts that can be incorporated into the design to improve the stack effect.**

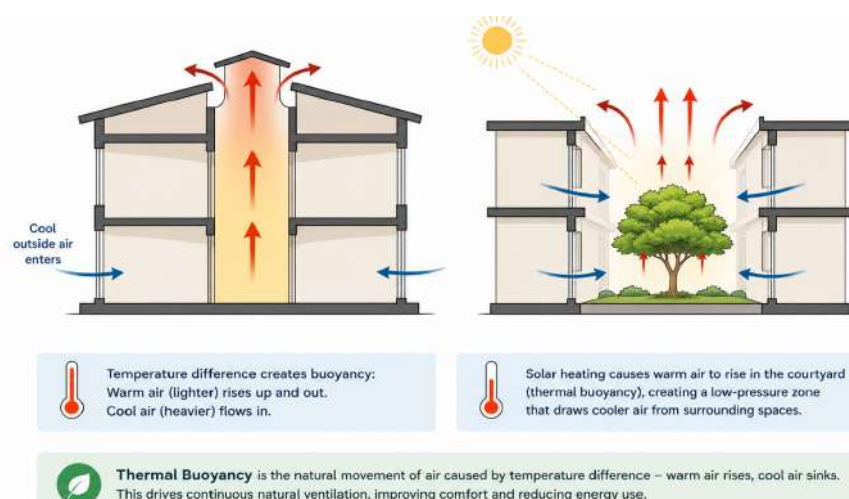


Figure 15: Stack ventilation and courtyard effect



Courtyard effect: A courtyard is an internal open-to-sky space that acts as a reservoir of cool air. During daytime, the sun-heated air inside the courtyard rises and is replaced by relatively cooler air from the outdoors. During nighttime, the courtyard collects cooled night air, which settles before gradually moving into surrounding rooms. This is most effective in the Hot-Dry climate zone with a strong diurnal temperature swing and can also be used in Composite climate zones.

Combined ventilation (wind + stack effect): This is the strongest natural ventilation mechanism combining the pressure and buoyancy effects together. This requires openings at both low and high levels of the building and on more than one façade.

Single-sided ventilation (openings on only one wall): This is comparatively less effective than cross ventilation and works only when the low and high openings are spaced far apart vertically.

Rules of Thumb for ventilation strategies:

- Orient inlet windows within approximately 30° of the prevailing wind direction.
- Make inlet openings equal to or larger than outlet openings to enhance air movement through the space.
- Set window sill height at approximately 0.75 m to bring airflow into the occupied (seated) zone.
- Provide operable window openings equal to at least 1/6th (about 16.7%) of the floor area of habitable rooms (Openable Window-to-Floor Ratio), opening directly to the exterior, to ensure adequate ventilation.
- For single-sided ventilation, keep room depth below about 2.5 times the ceiling height; for cross ventilation, room depth can extend to about 5 times the ceiling height.
- Avoid fully sealed internal partitions in double-banked layouts; provide high-level internal openings such as transoms and jaalis to maintain cross-ventilation paths between rooms.
- Use opening controls (louvers, operable sashes, canopies) to direct airflow and adjust ventilation rate to occupant comfort and weather conditions.

Ventilation requirements in the National Building Code (NBC), 2016, are intended to maintain adequate oxygen and carbon dioxide levels, and control body odours in spaces that do not contain combustion products or other contaminants. The NBC 2016 specifies minimum ventilation rates, defined as air change per hour (ACH) depending on the type and usage of indoor space.

3.1.4 Specialised Passive Cooling Techniques

Earth-Air Tunnels (Earth-Air Heat Exchangers): In this passive cooling technique, outdoor air is drawn through a tunnel or pipeline running below ground. Because underground temperature remain significantly cooler and steadier than surface temperatures throughout the year, incoming summer air is pre-cooled before it enters the building. A wind tower or scoop at the surface level outside the building captures the ambient air and directs it into the tunnel before it is supplied to the building.

Shading the ground above the tunnel or pipeline with vegetation and periodically wetting further lowers the underground temperature, adding an evaporative cooling effect as air



passes through the damp tunnel walls. This strategy is best suited to standalone buildings with adequate land and excavation depth for the tunnel or pipeline around the building, making it more feasible for standalone houses or campuses than densely built urban sites.

Passive Evaporative Cooling¹⁹: This technique uses wetted surfaces, such as water sprays or cooling pads to cool the ambient air, as is commonly seen in passive draught towers and everyday desert coolers. The ambient air cools down as the water absorbs heat from the surrounding air during evaporation. The resulting cool air is denser than the surrounding warm air, causing it to sink naturally into occupied spaces below without needing mechanical assistance. Passive evaporative cooling-based towers or openings are designed to let this heavier air settle into the occupied spaces.

Where evaporation needs to be actively controlled or boosted, for instance with a mechanical pump or fan, the system becomes a hybrid rather than a passive cooling technique. This strategy is effective mainly in Hot-Dry climates with low ambient humidity, where the air can absorb additional moisture. However, **effectiveness drops significantly in Warm-Humid climate zones, where air humidity is already close to saturation and evaporation is limited.**

Overview of the Passive Cooling Strategies:

Strategy	Primary mechanism	Design Stage and Remarks
Form and orientation	Reduces solar exposure and aligns with prevailing wind patterns	Early design stage; no/low cost; solar orientation takes precedence over wind orientation
Landscape and vegetation	Shading and evapotranspiration	Any stage; greater cooling benefit in drier climates
High thermal mass (walls/roof)	Absorbs and delays heat, releases heat at night	Early design stage or during construction; effective when diurnal swing is high (Hot-Dry climate zone)
Thermal insulation	Reduces conductive heat transfer	Construction / retrofit stage
Cool roofs	Reflects solar radiation	Construction / retrofit stage
Green roofs	Insulation and evapotranspiration	Construction / retrofit needs adequate structural capacity
Glazing (Low-E/IGU)	Reduces conductive and solar heat gain	Construction / retrofit stage
External shading (self-shading and shading devices)	Blocks direct/diffuse radiation before entry	Early design stage; low/no cost; sizing varies by latitude/orientation
Cross/stack ventilation	Wind pressure / buoyancy airflow	Early design stage; critical in Warm-Humid climate where thermal mass is not effective
Courtyard effect	Day/night thermal buffering	Early design stage
Earth-air tunnels	Ground-temperature pre-conditioning	Early design stage; most effective in Hot-Dry, implementable in Composite climate zone
Evaporative cooling	Heat loss through water evaporation	Any stage; effective in Hot-Dry climate only

¹⁹ Evaporative cooling is a cooling process that uses the physical effect of water evaporation as a natural heat sink. Heat is drawn from the surrounding air as water changes from liquid to vapour, which cools the air in the process.





Figure 16: Illustration of Passive Cooling Strategies and Low-energy Comfort Systems

3.2 | Building Material Options

The built environment in urban areas extensively uses heat-absorbing materials such as exposed concrete, metal sheeting, asphalt, and dark-coloured surfaces, which absorb and retain heat due to their high thermal mass and high solar absorptance. This increases indoor temperatures and raises thermal discomfort, which in turn compounds the UHI effect and can also cause a significant increase in cooling-related electricity consumption.

Opting for climate-responsive building materials is a cost-effective intervention to reduce a building's heat gain, improve indoor thermal comfort, lower cooling demand, enhance energy efficiency, and reduce reliance on mechanical cooling. Based on the climate zone of the building location, the principles for building material selection vary according to moisture conditions and diurnal temperature swings.

In hot and dry regions such as Rajasthan, Gujarat and Central India, ***high-thermal-mass materials that absorb heat slowly during the day and release it at night are preferred, allowing buildings to benefit from diurnal temperature swings.***

In warm and humid regions like Kerala, Goa, coastal Maharashtra, West Bengal, Odisha and the northeastern states, ***low-thermal-mass materials that do not retain heat and are breathable and lightweight are preferred as they support continuous cross-ventilation.***

Composite climate regions such as Delhi, Lucknow, Chandigarh, and Bhopal need building materials that balance these two approaches, including materials with moderate thermal mass, insulation materials, and cavity wall systems that reduce summer heat gain while retaining winter warmth.

3.2.1 Wall and Roof Materials

Choose the right building materials with suitable thermal transmittance or heat transfer coefficient (U-value) for envelope components such as walls, windows and roofs, gives better thermal performance and keeps the indoor temperatures comfortable. Materials such as Autoclaved Aerated Concrete (AAC) or Porotherm (hollow clay) blocks that may cost more per unit but can significantly improve indoor comfort level and reduce cooling load.



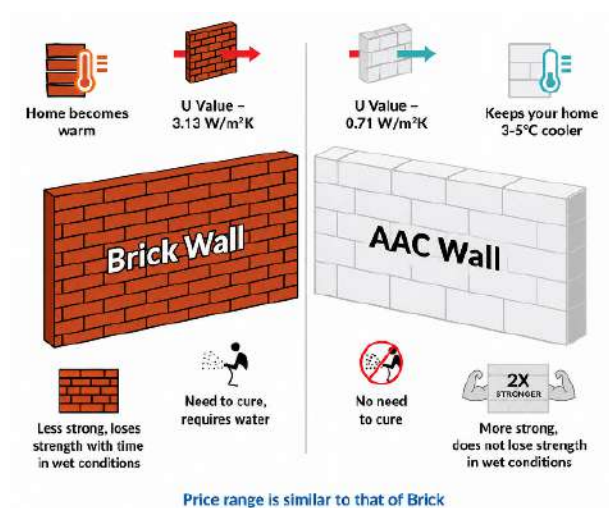


Figure 17: Comparison of clay bricks and AAC blocks for wall masonry

For low-rise (single/double-storey) buildings thermal insulation of roofs can be prioritised as roofs are the most solar-exposed surface in such buildings and **for multi-storey buildings, wall insulation should be prioritised as exposed wall area substantially exceeds roof area in such large scale buildings.** A building simulation study comparing wall/roof combinations found cooling load fell from 404 kW (plain 160mm RCC wall) to 64 kW with 200mm AAC block plus 50mm XPS insulation for roof, the best-performing combination tested²⁰.

In the same study, using a rat-trap bond masonry reduced the building's cooling load from 404 kW to 229 kW using the air gap alone, with no added insulation material. This makes rat-trap bond and cavity wall construction a useful middle-ground option where AAC block or insulated assemblies are not feasible and can also be used when a building design is to be optimised for both thermal performance and lower embodied carbon footprint in a project. However, these construction techniques cannot be treated as a substitute for use of building materials such as AAC blocks or insulation assemblies in high heat-stress applications.

Table 1 summarises wall and roof material options across the three heat-priority climate zones: Hot and Dry, Warm and Humid, and Composite. Locally available materials should always be prioritised where feasible, to reduce emissions from transportation and increase cost savings by reducing and support regional construction practices. A few industrially manufactured products listed in Table 1 are briefly explained here.

AAC blocks (Autoclaved Aerated Concrete): These are precast concrete blocks made by curing a mixture of cement, sand or fly ash, and an aerating (foaming) agent under heat and pressure in an autoclave. During this process, millions of tiny air pockets form within the material, making the blocks much lighter than solid concrete, while also improving their thermal insulation.

Porotherm / hollow clay blocks: These are factory-made clay blocks with a honeycomb pattern of internal perforations, unlike solid hand-moulded bricks. The hollow structure slows transfer of heat through the wall while also making the block lighter.

²⁰ ICLEI South Asia (2020). Guidelines for Energy Efficient and Climate Responsive Homes in Nagpur. <https://southasia.iclei.org/publication/guidelines-for-energy-efficient-and-climate-responsive-homes-in-nagpur/>



CSEB, including interlocking CSEB (Compressed Stabilised Earth Blocks): CSEBs are made by compressing locally available soil, sand, and a small proportion of cement or lime stabiliser in a hydraulic press, instead of firing the blocks in a kiln. Interlocking variants are made with tongue-and-groove profiles that allow the blocks to fit together accurately, reducing, and sometimes eliminating, the need for mortar.

Fly ash bricks: These bricks are made of fly ash (a by-product of coal-based thermal power generation), lime, and gypsum. Instead of being kiln-fired, these are compressed and cured. This process offers a lower-carbon alternative to conventional fired clay bricks.

Table 1: Wall and Roof material characteristics and suitability to climate zones

Material	Best-suited zone(s)	Suitability	Key thermal characteristics	Approx. cost (₹/unit)
Wall Materials				
Stone masonry (sandstone/local stone)	Hot-Dry	Very High	High thermal mass; delays heat transfer; durable	180–450/sq. ft
Adobe / mud blocks	Hot-Dry	Very High	Low conductivity; natural insulation	40–120/sq. ft
Compressed Stabilised Earth Blocks (CSEB), including interlocking (ICSEB)	Hot-Dry; Composite	High	Thermal buffering; low embodied energy; interlocking variants require little or no mortar, cutting costs ~15–20% compared with fired brick and reducing construction time	30–80/block
Porotherm / hollow clay blocks	Hot-Dry; Warm-Humid; Composite	High	Perforated clay; U-value as low as ~0.6 W/m²K (compared with ~1.8 for solid clay brick, ~2.0 for solid concrete block); approximately 60% lighter than solid concrete blocks	45–90/block
Bamboo wall systems	Warm-Humid	Very High	Lightweight, breathable, aids ventilation	120–350/sq. ft
Timber / wooden panels	Warm-Humid	Very High	Low heat retention; durable in humid conditions	250–700/sq. ft
Laterite stone masonry	Warm-Humid	High	Moderate insulation; moisture-resistant	160–350/sq. ft
Jali / ventilated wall systems	Warm-Humid	High	Enhances airflow; cuts heat buildup	150–500/sq. ft
Brick masonry with cavity wall	Composite	Very High	Air-gap thermal barrier across seasons	140–280/sq. ft
AAC blocks	Composite (also Hot-Dry/Warm-Humid)	High	Lightweight; air-void insulation	2,500–4,500/cu.m
Fly ash bricks	Composite	High	Lower conductivity; low-carbon	5–8/block
Hollow concrete blocks	Warm-Humid; Composite	Moderate-High	Internal cavities reduce conductive heat transfer	35–70/block
Lime plaster finish	All heat-priority zones	Moderate-High	Reflective and breathable; reduces solar heat absorption	25–60/sq. ft
Stone cladding + insulated wall system	Composite	Moderate	Thermal buffering on façades	250–700/sq. ft



Solid RCC / concrete walls (untreated)	All zones (least preferred)	Low	High heat absorption and retention	180–400/sq. ft
Roof Materials				
Clay tile roofing	Hot-Dry; Warm-Humid; Composite	High–Very High	Cuts direct solar gain; aids ventilation	80–180/sq. ft
Filler slab roofing	All heat-priority zones	High	Reduces roof heat gain and concrete use	180–350/sq. ft
Cool roof coatings / reflective finish	All heat-priority zones	High	Reflects solar radiation; lowers surface temperature	20–80/sq. ft
Insulated roof systems	All heat-priority zones (esp. Composite)	High–Very High	Cuts conductive transfer; balances summer/winter performance	150–350/sq. ft
Sloped/ventilated roof systems	Warm-Humid	Very High	Improves airflow and rainwater drainage	150–350/sq. ft
Bamboo/timber roof systems	Warm-Humid	High	Lightweight; low heat retention	180–500/sq. ft
Green roof systems	Composite	Moderate	Provides insulation while reducing surface heat gain	250–800/sq. ft
Lime concrete terracing	Hot-Dry	Moderate	Reflective; traditional flat-roof option	80–160/sq. ft
RCC roof (untreated)	All zones (least preferred)	Low–Moderate	High solar heat absorption if untreated	120–250/sq. ft
Metal sheet roofing	All zones (least preferred)	Very Low	Rapid heat transfer and indoor heat buildup	90–220/sq. ft

Note: This is an illustrative index and not derived from any specific field study. Costs are indicative and vary by location, material quality, transport, and labour.

3.2.2 Insulation and Reflective Materials

Roofs remain the most solar-exposed building surface and are typically the single largest contributor to indoor heat gain, especially in individual buildings. Adding thermal insulation to roofs, and if required, for walls and floors reduces the indoor heat gain in hot climatic zones. Effective thermal insulation can reduce indoor temperatures by approximately 2–5°C, leading to substantial reductions in cooling energy demand during peak summer periods.

In Composite and Hot-Dry climate zones, higher insulation is required to reduce the intense solar heat gain. In Warm-Humid climate zone, breathable materials with moderate insulation and moisture-resistance properties are preferred over heavier insulation, since trapped moisture is a bigger risk than heat gain in this climate zone. It is recommended to select thickness of insulation material based on the target U-value as applicable for compliance to codes or standards such as the ECSBC/ENS which specify minimum R-values for roofs and walls. The choice of insulation material will, however, depend on cost considerations. Table 2 provides a summary of thermal properties and cost for common insulation materials.



Table 2: Thermal properties and cost of common insulation materials [Source: ICLEI South Asia (2024)²¹]

Insulation Material (50 mm thickness)	Density (kg/m ³)	Thermal Conductivity (W/mK)	Material Cost (INR/Sqm)
Extruded Polystyrene (XPS)	30	0.0321	200–800
Expanded Polystyrene (EPS)	34	0.035	150–650
Rockwool (local make)	48	0.046	180–250
Rockwool (branded)	64	0.046	1,600–2,400
Glasswool	49	0.0351	250–1,000
Rigid Polyurethane (PUR)	40	0.0269	500–2,500
Polyurethane Foam (PUF) Spray	40	0.0372	650–1,000

Note: Costs are indicative and may vary depending on local context and market prices

Applying reflective materials to reduce heat gain from roofs, the Cool Roofs concept, is a cost-effective option for both new and existing building applications. For new buildings, the incremental cost of adding cool roofs is minimal. For existing buildings too, the additional expenses may be insignificant if the retrofit is properly integrated with the reroofing schedule. Reflective coatings can be reapplied every 7–10 years and can increase the longevity of the roof structure under it. Table 3 describes the common reflective materials and their costs.

Table 3: Cost of reflective materials for roof excluding installation cost [Source: ICLEI South Asia (2024)²²]

Cool roof application	Description	Material Cost (INR/Sqm)
Lime based White paint	Low-cost cool roof solution.	5 – 20
High SRI & Reflective paints	Offer a balance between cost and performance, being easy to apply and relatively affordable.	80 – 200
Cool roof Tiles	High-cost cool roof solution. High upfront costs but provide the best durability and long-term performance.	450 – 600

Note: Costs are indicative and may vary depending on local context and market prices

3.2.3 Emerging Materials for Heat Resilience

Several industrial building materials, such as Porotherm, hollow clay blocks and interlocking CSEB, are already commercially established in the Indian construction sector, with real cost and performance data from several projects developed over the last decade. Other materials are still in the early stages of adoption in India, with limited commercial application and few India-specific performance benchmarks.

While these emerging building material options have the potential to improve building heat resilience, they need to become commercially viable and be benchmarked in codes and standards before they can be used at scale. Unlike the materials listed in Table 1 and Table 2, the options listed below do not yet have India-specific performance benchmarks or standards

21 ICLEI South Asia. (2024). Technical Guideline for Heat-Resilient & Sustainably Cooled Buildings in Vijayawada City. <https://southasia.iclei.org/publication/technical-guidelines-for-heat-resilient-and-sustainably-cooled-buildings-in-vijayawada-andhra-pradesh/>

22 ICLEI South Asia. (2024). Technical Guideline for Heat-Resilient & Sustainably Cooled Buildings in Vijayawada City. <https://southasia.iclei.org/publication/technical-guidelines-for-heat-resilient-and-sustainably-cooled-buildings-in-vijayawada-andhra-pradesh/>



Phase Change Materials (PCMs): PCM-integrated building materials such as wallboards and plasters absorb heat as they melt at a set transition temperature and release it as they re-solidify, reducing indoor temperature fluctuations without increasing wall thickness. Recent research reports that using PCM in combination with conventional insulation results in longer-duration indoor thermal comfort. The performance of PCM is sensitive to its transition temperature and needs to be carefully selected based on local climatic conditions in which it will be used.

Aerogel insulation and vacuum insulation panels (VIPs): Aerogels and VIPs have high thermal resistance per unit of material thickness. For example, aerogels have a thermal conductivity that is below 0.035 W/mK, which is several times lower than conventional insulation materials. This makes them suitable for use in buildings where the wall or roof thickness is constrained, such as retrofits of heritage or narrow-plot structures. However, their high manufacturing cost, linked to their energy-intensive industrial manufacturing process, currently limits their widespread adoption in the Indian construction sector. Notably, fumed-silica-based composites are emerging as a lower-cost alternative with comparable insulating performance to aerogel insulation.

Hempcrete and other bio-based composites: Hempcrete, which is a lime and hemp plant shive composite, and other bio-based wall infill materials offer low embodied carbon, moderate insulation, and good moisture-buffering behaviour. They are increasingly being tested in pilot low-rise institutional construction internationally and are best suited for use as non-load-bearing material or infill applications within a structural frame.

Precast insulated sandwich panels: Precast insulated sandwich panels are factory-manufactured panels that consist of an insulation core between two concrete or fibre-cement skins, allowing for factory-controlled high thermal performance and faster on-site erection. These panels are useful for institutional and large-footprint buildings such as schools and hospitals.

Translucent Concrete: Translucent concrete embeds optical fibres or light-transmitting elements within the matrix of structural concrete, combining structural performance with daylighting function. This can reduce reliance on dedicated glazed openings in specific façade applications. This is a high-cost option in the Indian market and remains a niche technology.

Rice Husk & Fly Ash Bricks: These composite bricks are made by blending rice husk, which is an agricultural by-product from rice milling, with fly ash to produce bricks with lower thermal conductivity (0.44–0.55 W/mK) compared to standard fly ash bricks.

Plastic Waste & Fly Ash Bricks: Blending fly ash with shredded plastic waste (PET, PU, or PE) produces composite fly ash bricks with notably low thermal conductivity (0.15–0.41 W/mK) determined by the plastic type and proportion. Alongside a useful waste-diversion benefit for both coal ash and non-recyclable plastic. However, compressive strength drops as plastic content increases, often to as low as 3–5 MPa, which generally restricts current use to non-load-bearing partition walls rather than structural applications, and this too remains a research-stage material without established Indian commercial production or code benchmarking.



3.3 | Active Cooling Solutions

Active cooling solutions are the mechanical backstop when passive design strategies fail to maintain the required thermal comfort levels. Fans, desiccant systems, radiant cooling, and HVAC systems can be deployed to address the residual heat load that passive strategies and material choices cannot dissipate.

No combination of form, orientation, shading, and envelope performance can maintain comfortable indoor conditions throughout the year, particularly during extreme heat events. Active cooling systems are therefore required to close the gap rather than serve as the primary means of cooling. Because they consume significant amounts of energy, they should be selected and sized to minimise the cooling load they need to handle.

A building with strong passive design and materials needs a smaller, less energy-intensive active system than one that relies on mechanical cooling to compensate for poor design. The active cooling solutions described below range from low-energy thermal comfort measures that can extend the comfort range with minimal electricity use to full HVAC systems for spaces where mechanical cooling is unavoidable. These systems should be selected and sized in this order of priority, rather than defaulting to the most powerful available system.

3.3.1 Low-Energy Thermal Comfort Systems

Low-energy thermal comfort systems reduce reliance on full mechanical air conditioning and work well alongside passive design strategies.

Ceiling Fans: Ceiling fans aid indoor air movement and improve the physical cooling effect. They can lower the 'felt' air temperature by roughly 2–4°C, allowing the occupants to set higher thermostat temperatures when air conditioning is used alongside them. Since fans account for a significant share, roughly 30–40%, of the total building electricity use, fan efficiency is an important lever for reducing energy consumption. Choosing energy-efficient ceilings fans therefore improves thermal comfort while reducing energy consumption. Brushless Direct Current or BLDC fans are the most efficient mainstream option available today. They consume roughly 28–30 W, compared with 50–70W for conventional fans. This is about 63% more efficient than a non-star-rated fan and 36% more efficient than a 5-star AC motor fan, while costing roughly the same.

Desiccant Cooling Systems: Desiccant cooling systems rely on a heat-driven cycle rather than an electricity-driven one. Air is dehumidified using a moisture-absorbing desiccant before being cooled, making it well suited to humid climates where humidity control is as important as temperature reduction. The desiccant material can be regenerated using low-cost heat sources such as solar energy, waste heat, or natural gas, reducing electricity consumption compared with conventional air conditioning systems. These systems are more suitable for large-scale applications, such as pharmaceutical facilities, supermarkets, and cold storage, rather than individual homes, because the desiccant wheel needs frequent regeneration and monitoring to operate efficiently.

Desiccant cooling is particularly effective in warm-humid climates, making it well-suited to India's extensive coastal regions. When integrated with solar energy, it offers a highly efficient



solution fo

lity control.

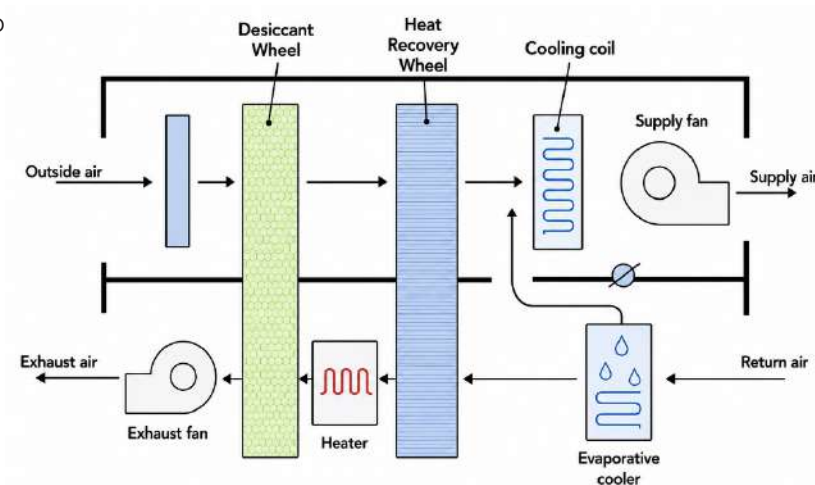


Figure 18: Dessicant Cooling System [Source: Rawal et al. (2022)²³]

Radiant Structural Cooling: In this active cooling solution, chilled water is circulated through hydronic circuits embedded in floors, ceilings, or walls, cooling indoor spaces by absorbing heat from occupants and surfaces through radiant heat exchange rather than by blowing cooled air through ducts and fans. Since there are no ducts or fans involved, the system operates quietly and minimises the recirculation of dust or allergens.

Humidity control is essential to avoid condensation on cooled surfaces, particularly in humid climates, and the system requires continuous power to maintain the required surface temperatures. Radiant structural cooling is best suited to commercial offices, institutions, high-end residential projects, and healthcare facilities, where consistent comfort and low noise are priorities.

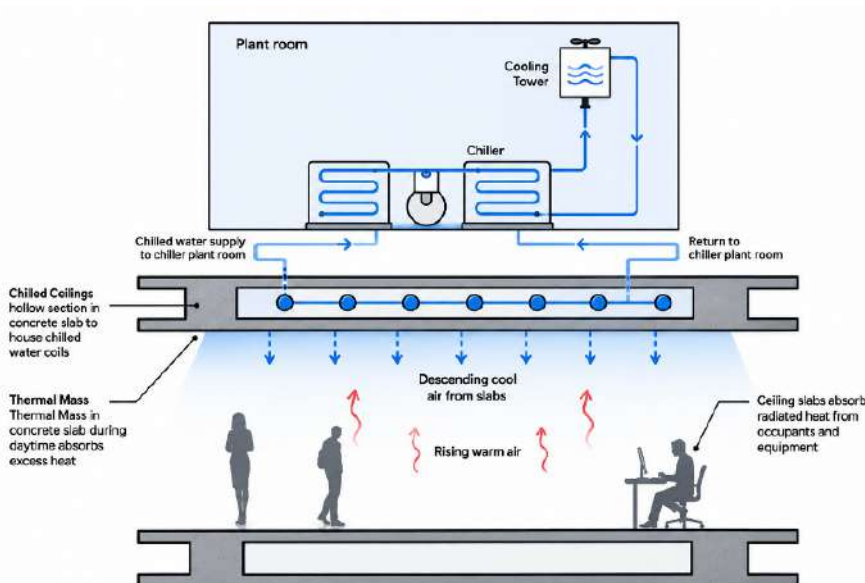


Figure 19: Radiant Cooling System

²³ Rawal, R., Pathak, B., & Shukla, Y. (2022). Climate smart buildings: Training program on innovative construction technologies & thermal comfort in affordable housing



3.3.2 HVAC Systems

Direct Expansion (DX) Packaged Systems: DX systems cool air through the vapour-compression refrigeration cycle, the mechanism used in most conventional air conditioning systems. A refrigerant absorbs heat directly from indoor air as it passes over the cold evaporator (cooling) coil, changing from a liquid to a gas. The compressor then pressurises this refrigerant gas, raising its temperature, before it moves to the condenser coil, where the absorbed heat is released outdoors and the refrigerant condenses back into a liquid. This cycle is repeated continuously, with the refrigerant absorbing heat from indoor spaces and rejects it outside. No intermediate fluid such as chilled water is involved, which is what distinguishes DX systems from chilled water systems.

Unitary air conditioners or Window ACs are compact and self-contained air-conditioning units that can cool individual rooms. They are cost-effective for homes, small offices, and hotel rooms, though their energy use per unit area is relatively higher at scale. Split air-conditioners have separate indoor and outdoor units. The outdoor unit houses the compressor and condenser and the indoor unit the houses the evaporator coil (cooling coil) and blower fans. These are the most common systems used for individual rooms and small commercial spaces. Packaged air

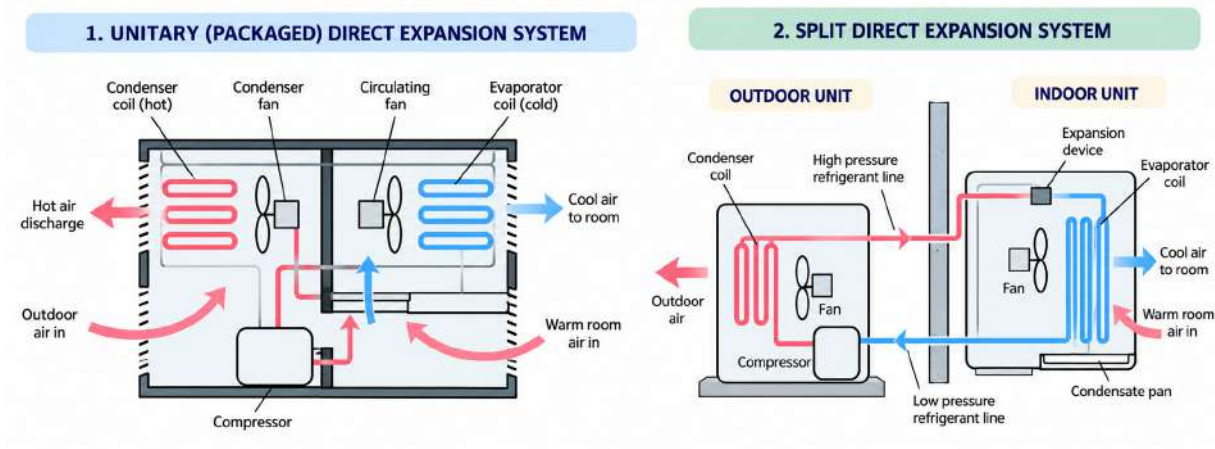


Figure 20: Direct Expansion Packaged Cooling Systems

Chilled Water Systems: Chilled water systems use water as the heat-transfer medium instead of circulating refrigerant directly through occupied spaces. A central chiller cools water to about 6–7°C, which is then circulated through insulated pipes to air-handling units (AHUs). There the chilled water absorbs heat from indoor air before returning to the chiller to be cooled again. Since the cooling is centralised at the chiller and distributed using water, chilled water systems are better suited to large buildings, industrial facilities, and commercial complexes than to individual rooms, where the direct expansion systems remain more practical.

Chillers reject the heat absorbed from the building depending on how they are designed, the cooling load, and the availability of space in buildings. Air-cooled chillers reject heat directly to the ambient air, require relatively little maintenance, and are well suited to sites with limited space and water supply. They typically range from 15 to 1,000 tons (53 to 3,500 kW) in cooling capacity.



In contrast, water-cooled chillers use water, circulated through cooling towers, to reject heat, offering higher efficiency and capacity than air-cooled systems. But they require careful water treatment to prevent scaling and corrosion, making them best suited to sites with a reliable water supply and enough space to install all the required sub-systems.

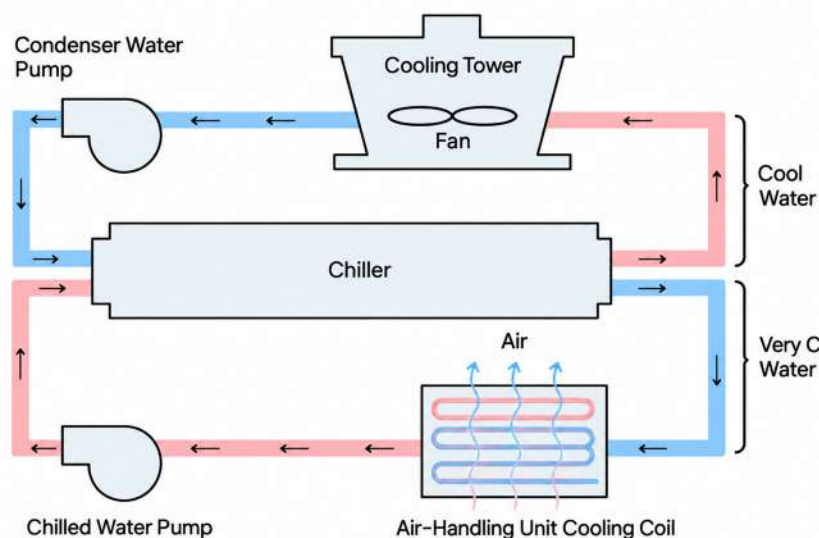


Figure 21: Chilled Water Cooling Systems

Variable Refrigerant Flow (VRF) Systems: VRF systems operate on the same vapour-compression cycle as a DX system. The refrigerant absorbs heat at the indoor evaporator coil and rejects it through an outdoor condenser. However, VRF systems intelligently distribute the condensed refrigerant from the outdoor unit to many indoor units, instead of running one fixed refrigerant circuit per unit. Inverter-driven compressors in the outdoor unit continuously adjust their speed and refrigerant flow rate in response to the real-time cooling demand from each connected indoor unit, rather than switching on and off at a fixed capacity like conventional compressors. This allows the system to deliver only the amount of refrigerant required by each cooling zone at any given moment.

In heat-recovery configurations, refrigerant that has absorbed heat from a zone requiring cooling can be routed to a zone requiring heating instead rejecting that heat outdoors. This allows the system to move heat between zones, thereby achieving much higher efficiency. As a VRF system distributes refrigerant directly to each zone, rather than air through ducts, it avoids ducted air-distribution losses, typically estimated at 10–20% of the total airflow in ducted systems. This improves overall system efficiency.

The modular design of VRF systems suits both new construction and retrofits, making them particularly well suited to mixed-use buildings with varying zone-level temperature requirements, where different areas may require heating and cooling at the same time.



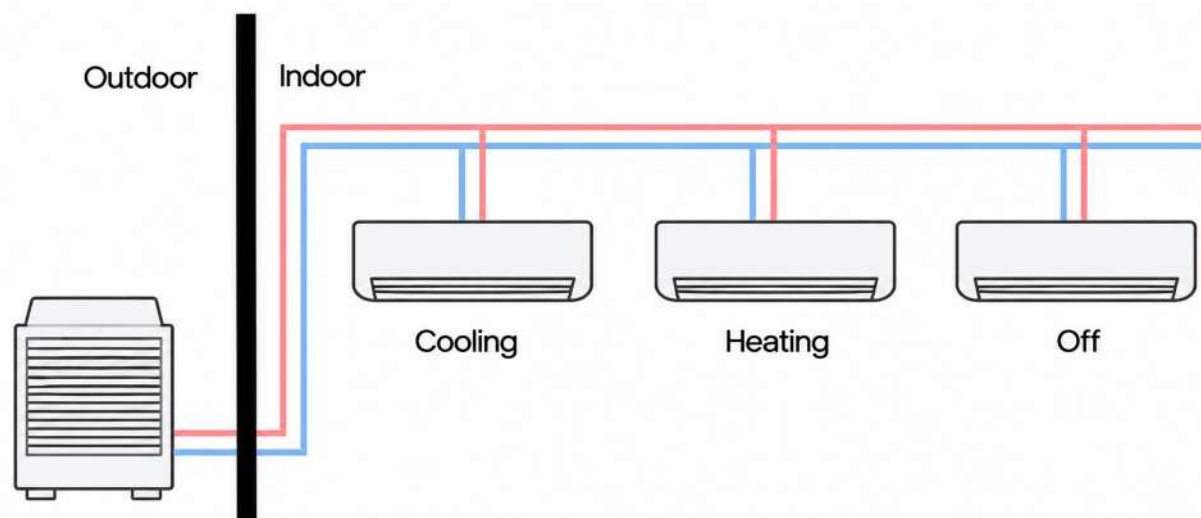


Figure 22: Variable Refrigerant Flow (VRF) Cooling Systems

Cost comparison of HVAC systems: Table 3 presents a comparative analysis of the costs associated with the HVAC systems discussed above. Capital costs encompass installation and setup expenses, while operational costs include energy consumption and maintenance. Life cycle cost represents the total investment over the system's lifespan, factoring in return on investment (ROI). The costs show that chilled water system has the highest initial cost but delivers the lowest life cycle cost, making it the most cost-effective option in the long run due to superior energy efficiency and long-term savings.

Table 4: Cost comparison for HVAC systems [Source: ICLEI South Asia (2024)²⁴]

	DX Packaged System	Chilled Water System	VRF System
Capital Cost (INR/sqm)	1,948	3606	2497
Operational Cost (INR/sqm)	721	366	603
Life Cycle Cost (INR/sqm)	1001	549	807

Note: Costs are indicative and may vary based on the local context and market prices

24 ICLEI South Asia. (2024). Technical Guideline for Heat-Resilient & Sustainably Cooled Buildings in Vijayawada City. <https://southasia.iclei.org/publication/technical-guidelines-for-heat-resilient-and-sustainably-cooled-buildings-in-vijayawada-andhra-pradesh/>



04 Nature-based Cooling Solutions for the Urban Built Environment

Nature-based solutions (NbS) are defined as “actions to protect, manage and restore natural or modified ecosystems, which address societal challenges, effectively and adaptively, providing human well-being and biodiversity benefits”.²⁵

Incorporating nature-based cooling solutions in urban built environments plays an important role in providing shade, reducing heat through evapotranspiration and serving as heat sinks, thereby lowering building temperatures. Green facade elements such as green roofs and vertical gardens cool buildings through evapotranspiration, shading, and reflection of solar radiation. They also reduce the penetration of ambient warm air into building facades.

Studies show that temperatures of walls with green facades were 3.5°C cooler than those without²⁶ and well-maintained green roofs can reduce building roof top surface temperature temperatures by up to 15 °C and reduce cooling loads by 70%.²⁷ The cooling potential of NbS can vary by type and context, and a few solutions are explained in detail below.

4.1 | Building-scale strategies

4.1.1 Green roofs

Green roofs are vegetated roofing systems that provide thermal comfort while improving stormwater retention and air quality. By adding a layer of vegetation and growing medium over the roof surface, they reduce the amount of solar heat absorbed by the building envelope, moderating indoor temperatures and lowering cooling demand compared to a conventional exposed roof. Beyond their thermal benefit, green roofs slow and reduce stormwater runoff by retaining rainfall in the growing medium, and improve local air quality by filtering particulate matter and absorbing pollutants through plant foliage, making them a multi-benefit intervention rather than a heat resilience focused one. A green roof design comprises the following layers:

Deck layer: This is the foundation of the green roof and can be made of concrete, wood, plastic, gypsum or a composite material. This layer determines the load-bearing capacity, strength and longevity of the green roof system. The deck layer can sometimes be followed by a leak detection system to identify and minimise leaks.

Waterproofing layer : This layer should be 100% waterproof and can include hot-applied rubberised asphalt, built-up bitumen, modified bitumen, thermoplastic membranes, polyvinyl chloride (PVC), thermoplastic olefin membrane (TPO), and elastomeric membranes (EPDM).

25 IUCN (2020). Nature-based Solutions: From Concept Definition to Global Standard. https://iucn.org/sites/default/files/content/documents/2021/nbs_from_concept_definition_to_global_standard_emmanuelle_cohen-shacham.pdf

26 Bakhshoodeh et al. (2021). Thermal performance of green façades: Review and analysis of published data. <https://doi.org/10.1016/j.rser.2021.111744>

27 Mihalakako et al. (2023). Green roofs as a nature-based solution for improving urban sustainability: Progress and perspectives. <https://doi.org/10.1016/j.rser.2023.113306>



Insulation layer : This layer is usually above or below the waterproofing layer, and provides thermal insulation and protection for the roof deck. This can be either open- or closed-cell insulation depending on moisture exposure.

Root barrier: This layer prevents root penetration into the waterproofing layer and can be made from durable materials like HDPE or PVC.

Drainage layer: This is a protective layer between the root barrier and growing media to remove excess water from the vegetation root zone. The thickness of the drainage layer should be chosen based on the stormwater retention capacity requirement and the rooftop's structural capacity. It usually varies from 0.25 to 1.5 inches for extensive green roofs, increasing for intensive designs.

Root-permeable filter fabric : A semi-permeable needled polypropylene filter fabric that prevents the growing media from clogging the drainage layer. Care must be taken to ensure that the filter fabric does not impede water flow into the drainage layer.

Growing media : For extensive green roofs, the growing media is typically composed of 70 to 80 per cent lightweight inorganic materials, such as expanded slates, shales or clays, pumice, scoria, or other similar materials. The media must contain no more than 30% organic matter, usually compost, to prevent clogging of the permeable filter fabric and a maximum water retention capacity of 30%.

Plant cover : Plant selection for green roofs is an integral design consideration, which should be selected based on local climate conditions and roof type. The plants must be resistant to extreme wind, heat, and cold and should be chosen based on building height, layout, wind exposure, and sun orientation.



Figure 23: Green roof design

Types of green roofs include:

Extensive green roofs: These are shallow green roofs, with a growing medium usually 2 to 6 inches thick. They are lightweight, low-maintenance, and usually designed for ecological benefits rather than public access.



Semi-intensive green roofs: They are slightly heavier than extensive green roofs, with a growing medium 6 to 12 inches deep that supports small shrubs and grasses. This roof type is more stable, retains more stormwater, and supports richer biodiversity, requiring moderate maintenance.

Intensive green roofs: These roofs include complex vegetation and intensive landscaping, often resembling roof gardens, with shrubs, large perennials, and tropical or non-native plants. With a growing medium depth greater than 12 inches, they often require extensive maintenance and are accessible to the public.

Table 5: Types of Green Roofs and their characteristics [Source: [Green Roof Technology](#)]

Green roof type	Extensive	Semi-intensive	Intensive
Purpose	Stormwater retention, biodiversity enhancement	Stormwater retention, biodiversity enhancement	Stormwater retention, biodiversity enhancement, public amenity
Vegetation type	Moss, herbs, grass	Grass, shrubs	Lawns, trees, and perennials
Overall depth	2–6 inches	6–12 inches	>12 inches
Average weight range	100–200 kg/m ²	120–300 kg/m ²	220–800 kg/m ² +
Maximum stormwater retention capacity	50–100 mm	75–110 mm	Over 120 mm
Cost	₹ 8,000–₹16,000/sqm	₹15,000–₹20,000/sqm	₹21,500–₹43,000/sqm
Irrigation system	Not recommended	Partially	Required

Design considerations for green roofs:²⁸

Green roofs are ideal for commercial, residential, or municipal buildings. The following key elements must be factored in while designing green roofs:

- **Structural capacity of the roof:** Designers must account for the structural capacity of the roof to support the weight of the additional green roof and water. Conventional roofs must be designed to support an additional 100–800 kg/m², based on green roof type.
- **Roof pitch (slope):** Green roofs are best placed on flat roofs (pitch of 1–2%). Roofs with greater slopes (up to 30%) can be used if buffers, such as grids or strips, are in place to prevent slippage of growing media.
- **Roof access:** The roof must be accessible for delivery of construction materials and regular maintenance work. Additional storage areas can also be identified to store green roof materials, depending on the roof's structural capacity.
- **Roof type:** Green roofs can be placed on most roof types, except in certain cases such as exposed treated wood or uncoated galvanised metal, due to the risk of pollutant leaching.
- **Setbacks:** Green roofs must not be located close to HVAC and electrical systems. A minimum

²⁸ Center for Watershed Protection. (2020). Stormwater management guidebook (Prepared for the District of Columbia Department of Energy and Environment). <https://doee.dc.gov/swguidebook>



two-feet-wide vegetation-free zone along the roof perimeter and a one-foot-wide vegetation-free zone around roof penetrations is required for fire safety.

- **Local building codes:** The green roof must comply with local building bye-laws and green building norms.

A green roof must be inspected by a professional at least twice a year to check for leaks, drainage and rooftop structural issues. Dead vegetation and invasive weeds must also be regularly removed. Localised roof leaks must be identified and repaired immediately. It is also advisable to avoid chemical pesticides and herbicides as they may degrade the waterproofing membrane.

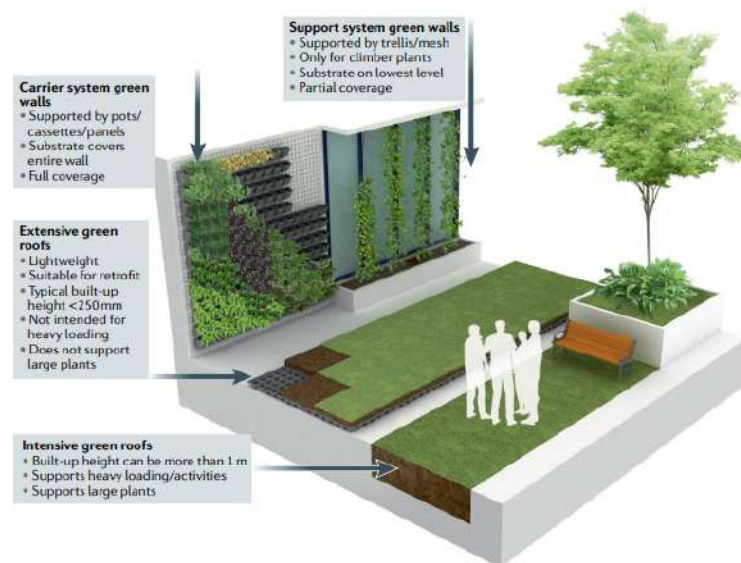


Figure 24: Different options for vertical and rooftop greenery [Source: Wong et al. (2021)²⁹]

4.1.2 Vertical Gardens and Green Walls

Vertical gardens consist of vegetation grown on vertical structures, walls, or frames. These gardens can be created on building facades, balconies, living room walls or small corners. Approximately 30–50 % facade coverage with vertical gardens is required to achieve an average temperature reduction of **1°C**.³⁰ Vertical greenery can also reduce cooling energy consumption by 5.9%.³¹ The various types of vertical gardens and green walls include:

- Green facades (climbing plants):** A type of green wall system in which climbing plants are trained to cover specially designed supporting structures on walls. Plants may be rooted in the ground or grown in elevated containers (e.g., pregrown trays, boxes, or tiles, mounted on a frame).
- Indoor green walls or living walls:** Comprises pre-vegetated panels or planted blankets fixed to a wall or frame. These panels can be made of plastic, expanded polystyrene, or synthetic fabric and can support a variety of plant types.
- Free-standing:** Independent vertical frames with planters that are not attached to walls

²⁹ Wong et al. (2021). Greenery as a mitigation and adaptation strategy to urban heat. <https://doi.org/10.1038/s43017-020-00129-5>.

³⁰ Morakinyo et al. (2019). Thermal benefits of vertical greening in a high-density city: Case study of Hong Kong. *Urban Forestry & Urban Greening*, 37, 42–55. <https://doi.org/10.1016/j.ufug.2017.11.010>

³¹ Che, W., Zhuong, W. (2024). Integrating vertical greenery for complex building patterns towards sustainable urban environment. <https://doi.org/10.1016/j.scs.2024.105684>



- d. **Trellis garden:** A vertical or horizontal latticed structure (trellis) that supports vertical and horizontal plant growth. Mainly used for climbers like ivy and bougainvillea.
- e. **Hydroponic vertical garden:** This uses a vertical support structure with a nutrient solution instead of soil. They are used to optimise space, water and nutrients, particularly for small urban areas. Hydroponic gardens can also use a fabric medium for indoor installations.

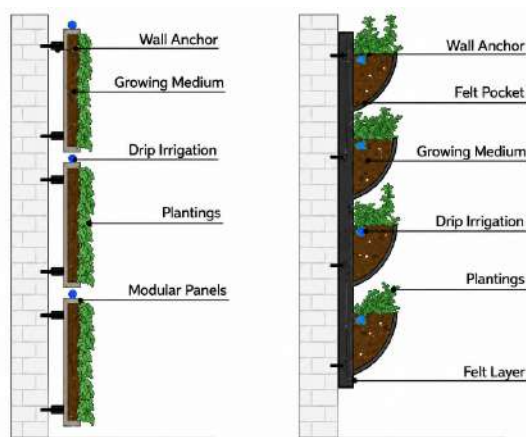


Figure 25: Green walls and Trellis [Source: Hadba et al. (2024)³²]

Design considerations for vertical gardens:

- **Structure:** Ensure the wall's structural stability all and place a waterproof barrier between the garden and the wall.
- **Accessibility:** Ensure accessibility to the planters for maintenance and pruning.
- **Light:** Choose plants based on sun and wind exposure on the façade.
- **Invasive plants:** Regularly remove invasive plants as they may damage the building's walls.
- **Irrigation:** Install irrigation systems (automated drip irrigation is the most common). This must be accompanied by a drainage system.
- **Average Costs³³:** Installation costs can range from ₹ 300 to ₹ 1,500/sq. ft, with maintenance costs ranging from ₹ 2,000 to ₹ 5,000 for pruning and ₹ 1,000 to ₹ 3,000 for irrigation systems.

4.2 | Neighbourhood-Scale Strategies

4.2.1 Tree Cover and Urban Shading

Street trees significantly improve thermal comfort by influencing air temperature, humidity, wind flow, and mean radiant temperature. Their cooling performance, however, depends on placement, species characteristics, and urban context.³⁴

1. The cooling effect of trees is influenced by their distance from building walls, with optimal cooling achieved when trees are planted 3–5 m from building walls.
2. The cooling effect depends on the ratio of tree distance from the shaded wall to building height, with the highest thermal comfort at a ratio range of 0.55–0.7. Cooling effectiveness

³² Hadba, L., Di Bitonto, M. G., Oliveira, M., Mendonça, P., Zanelli, A., & Silva, L. T. (2024). A nature-inspired green-blue solution: Incorporating a fog harvesting technique into urban green wall design. <https://doi.org/10.3390/su16020792>

³³ Gardening Tips (2025). How much does a vertical garden cost in India: The detailed cost breakdown. <https://gardeningtips.in/how-much-does-a-vertical-garden-cost-in-india>

³⁴ Kim et al. (2024). The cooling effect of trees in high-rise building complexes in relation to spatial distance from buildings. <https://doi.org/10.1016/j.scs.2024.105737>



3. drops by 9–29% when this ratio falls below 0.3, emphasising strategic placement of trees as a key factor.
4. Small trees can have a similar influence on thermal comfort comparable to that of larger trees, if placed at the correct distance
5. The cooling effect of different species varies due to leaf size, transpiration rates, and canopy spread. Thermal comfort increases with leaf area density, generally higher with dense foliage ($>2.5 \text{ m}^2/\text{m}^3$). However, very high canopy cover can also create localised heat pockets.

For maximum thermal cooling impact, urban tree planning should specify species selection, placement relative to buildings, and planting density and spacing, tailored to the surrounding built form and street geometry.

Tree shade has been found to reduce building LSTs **by 2–20 °C**.³⁵ A 2023 study across 35 Chinese cities showed that LST in tree-covered areas was **2.23°C lower** than in surrounding built-up areas during summer, thereby mitigating the UHI effect.³⁶

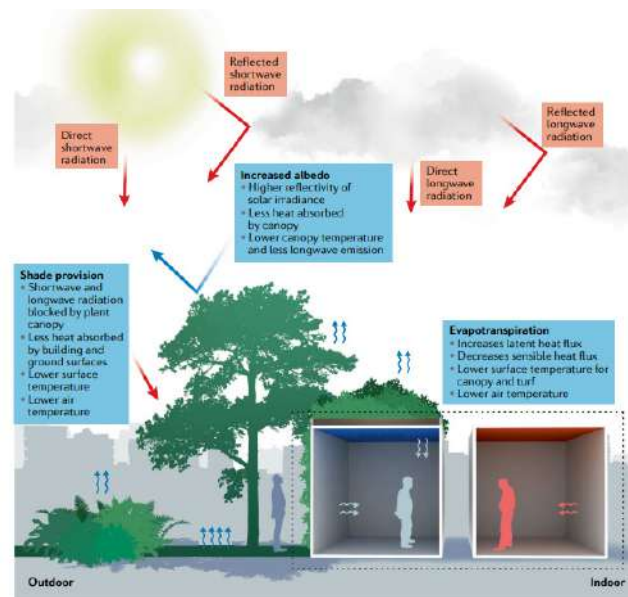


Figure 26: Effect of shading on microclimate [Source: Wong et al. (2021)³⁷]

4.2.2 Water Features for Cooling Effect

Pools, ponds, or fountains placed immediately outside windows or within internal courtyards pre-cool incoming air before it ever enters the building, since evaporation from the water surface draws heat from the surrounding air as it passes over. Water features can lower ambient temperatures through evaporative cooling of air and convection mechanism when applied at a landscape feature scale and can be combined with a courtyard design for a compounding cooling effect. As with other evaporative cooling strategies, this works well in Hot-Dry climates that have low ambient humidity. In Warm-Humid climate zones, the same water feature can

35 Son et al. (2025). Thermal mitigation effects of building and tree shade in a high-rise and park-dense urban area. <https://doi.org/10.1016/j.scs.2025.107073>

36 Guo et al. (2023). Contribution of urban trees in reducing land surface temperature: Evidence from China's major cities. <https://doi.org/10.1016/j.jag.2023.103570>

37 Wong et al. (2021). Greenery as a mitigation and adaptation strategy to urban heat. <https://doi.org/10.1038/s43017-020-00129-5>.



add moisture to the already-humid air, delivering negligible cooling effects and increased discomfort.

Water bodies in the vicinity of a building can reduce daytime surface temperatures by up to **3°C**, with a cooling radius of 800m from the water body's edge.³⁸ The cooling efficacy of water bodies depends on their size, shape and location.

- Larger water bodies provide more cooling, with maximum cooling impact within approximately 500m of the water body's edge.
- A study on the cooling potential of 12 water bodies in Bengaluru found that the water cooling range in summer was between 120m and 330m and the water cooling intensity varied between 1.29 °C and 2.71 °C.³⁹
- Areas with both water bodies and urban greening have synergistic cooling effects, creating cooler microclimates.

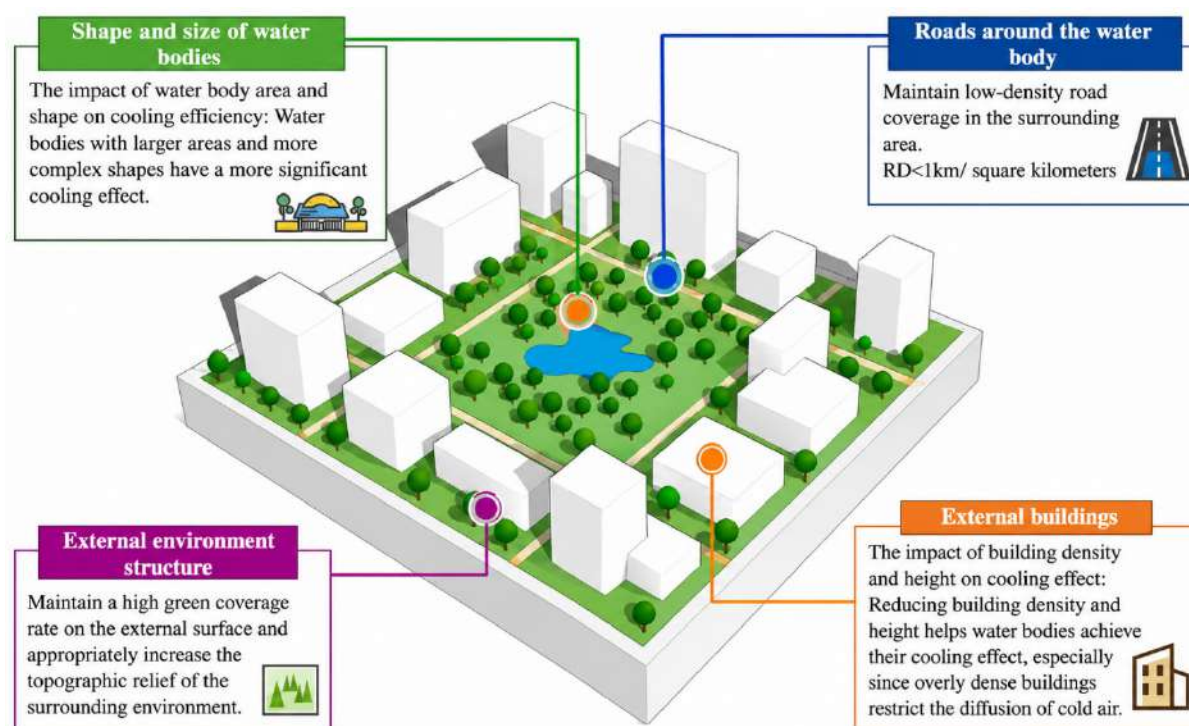


Figure 27: Water body planning and design strategies [Source: Liu et al. (2026)⁴⁰]

38 Jandaghian, Z., & Colombo, A. (2024). The role of water bodies in climate regulation: Insights from recent studies on urban heat island mitigation. <https://doi.org/10.3390/buildings14092945>

39 Verma, A., Agrawal, S. (2024). Evaluating the natural cooling potential of waterbodies in dense urban landscape: A case study of Bengaluru, India. <https://doi.org/10.1016/j.uclim.2024.102200>

40 Liu et al. (2026). Evaluating urban water body cooling effects and exposure at high spatial resolution: A case study in Guangzhou. <https://doi.org/10.1016/j.uclim.2026.102825>



05 Strengthening Governance for Heat Resilience in Buildings

Governance instruments, when applied together, enable the implementation of building-level heat resilience strategies. While building codes and standards set minimum design and performance requirements that any building must meet, once they are adopted by a state or ULB, Heat Action Plans (HAPs) identify where, for whom, and in what sequence heat resilience interventions, including building retrofits, should be prioritised across a city.

In short, codes and standards define how a building should perform, whereas HAPs define where that performance matters most and how interventions should be prioritised, financed and monitored. The two governance instruments are discussed further in the following sections.

5.1 | Building Codes and Standards for Heat Resilience in Buildings

Several mandatory and voluntary building codes, standards, and policies in India provide guidance on integrating passive and active cooling measures, along with thermal comfort considerations, into building design, construction, and operation. These frameworks promote climate-responsive and energy-efficient urban planning across different building types and climatic zones. The following table presents an overview of key national and state-level policies and building guidelines, highlighting the specific heat-resilience provisions and strategies included in each. Government officials, urban planners, architects, engineers, etc., can use these guidelines to design heat-resilient buildings and support compliance with applicable codes and rating systems.

Document	Document overview	Inclusions on heat resilience
Energy Conservation and Sustainable Building Code (ECSBC) for commercial and office buildings, Bureau of Energy Efficiency, 2024	Norms and standards for energy-efficient and green buildings, which become mandatory if adopted by states or cities. The code is applicable for commercial buildings with a connected load of ≥ 100 kW. The code specifies tiered compliance guidelines for ECSBC, ECSBC Plus and Super ECSBC buildings.	<ul style="list-style-type: none"> • Preservation of trees and compensatory plantation in the ratio of 1:3. • Paved area guidelines: not to exceed 30% of total site area excluding building footprint. • Heat island reduction in non-roof areas: For all super ECSBC buildings, structural shade shall be provided for 100% of the parking area, meeting cool roof criteria of a minimum SRI of 82. Additionally, 100% of the paved area shall incorporate a combination of heat island reduction measures, including shading from existing/transplanted trees, open-grid pavers or grass pavers, and hardscape materials with $29 < \text{SRI} < 64$. • Building envelope guidelines on parameters such as U-factor, Solar Heat Gain Coefficient, Visible Light Transmittance, Window-to-Wall Ratio, etc., for fenestration, daylighting, roofs, and external walls. • Mandatory requirements for thermal comfort systems such as ventilation, space cooling, piping, fans, chillers, etc. • Mandatory thermal comfort requirements for air velocity, relative humidity, level of activity and operative temperature. • Adaptive thermal comfort equations for acceptable indoor temperatures.



National Building Code, 2016 (Volume 2, Part 11)	Comprehensive model code providing guidelines for design, construction, maintenance, and safety (fire, structural, health) of buildings. While voluntary, it becomes mandatory if adopted by local authorities.	<ul style="list-style-type: none"> • Recommendations for building orientation and shading (adequate vertical shading, especially on eastern and western facades; building envelope protection against thermal losses, winds, rain, etc.). • Mandate to conduct building orientation and shading studies for each new project and implement strategies to ensure that building facades are shaded over more than 50 per cent of the summer solstice period. • Ventilation and cooling studies for all new building projects with strategies to enhance airflow and natural ventilation, particularly for high-rise buildings • Strategic vegetation near buildings based on shading patterns. Trees, shaded trellises, green roofs, green facades, and green walls may be used individually or in conjunction with other measures to increase shading on the ground and the building surface. • Use of shading or high-albedo materials for open parking areas: A minimum 50% of the total paved area (including parking) shall have shading by vegetated roof/ pergola with planters or a minimum 50% of the total impervious paving area (including parking) shall be topped with a finish having solar reflectance of 0.5 or higher. • Recommendation to include roof gardens or vertical gardens • Strategies to enhance thermal performance of walls, roofs, fenestration, floors, and surface finishes. • Sustainable alternatives for structural building materials • Strategies to enhance natural and mechanical ventilation • Guidelines for maintenance of Heating, Ventilation and Air Conditioning (HVAC) systems
India Cooling Action Plan (ICAP), 2019	A 20-year roadmap for sustainable, energy-efficient cooling across sectors, aiming to achieve a 25–40% reduction in cooling energy demand by 2037–38.	<ul style="list-style-type: none"> • Targets for reducing cooling demand across sectors including residential and commercial buildings. • Strategies to optimise cooling demand through passive building envelope measures • Interventions to improve energy efficiency of cooling equipment and operations
Energy Conservation Building Code (ECBC), 2017	Standard that sets minimum energy performance criteria for commercial buildings at the ECBC, ECBC+ and Super ECBC levels.	<ul style="list-style-type: none"> • Recommendations on roof insulation, wall thermal transmittance, shading, glazing, passive design, and HVAC cooling efficiency • Heat resilient and energy efficient building envelope standards for different climate typologies
Eco Niwas Samhita (ENS) 2024	Voluntary energy conservation and sustainable building code applicable for residential buildings or building complexes with a minimum connected load of 100 kW. Includes criteria for 3 levels of compliance: ENS, ENS+ and Super ENS	<ul style="list-style-type: none"> • Building envelope standards for improved thermal comfort: window-to-floor area ratio, ventilation, thermal transmittance of roof, and visible light transmittance • Preservation of trees and compensatory plantation in a ratio of 1:3 • Prescribes limiting net paved area to 25% of site area for reducing urban heat island effect. • Minimum efficiency requirements for electro-mechanical cooling equipment and fans under Part II, relevant to overall building heat resilience where passive measures alone are insufficient.



Indian Green Building Council (IGBC) Green New Buildings, 2025	Fee-based green building rating and certification system for new commercial buildings	<ul style="list-style-type: none"> • Prescribes point-based criteria for • Sustainable landscape and vegetated spaces including green roofs • Cool roofs and non-roof impervious areas • Energy-efficient building envelope • Cooling capacities of space conditioning systems • Passive design elements • Low-embodied carbon materials
Green Rating for Integrated Habitat Assessment (GRIHA) version 6.0, 2025	National green building rating system developed by The Energy and Resources Institute and endorsed by the Ministry of New and Renewable Energy for new and existing buildings	<ul style="list-style-type: none"> • Prescribes point-based criteria for: • Site planning and climate-responsive design to reduce heat gain • Thermal comfort through building envelope optimisation (U-values, shading, and insulation) • Passive design strategies such as orientation, natural ventilation, and daylighting • Use of cool roofs, high-albedo materials, and reduction of heat island effect • Energy efficiency in space conditioning systems and reduced cooling demand • Integration of renewable energy systems • Sustainable materials with low environmental and thermal impact • Water-sensitive design and landscape strategies that contribute to microclimate cooling
Bureau of Energy Efficiency Star Rating for Buildings, 2009	Voluntary rating system (1-5) for commercial buildings based on energy efficiency	Does not explicitly include heat-resilience components, but a reduction in cooling energy demand will contribute to higher ratings. The Star Rating and Shunya Labelling programmes for commercial and residential buildings have been suspended, pending revision.
Energy Conservation (Amendment) Act, 2022	Central legislation amending the Energy Conservation Act, 2001. Empowers the Union Government to mandate compliance with energy conservation building codes, including ECSBC/ECBC and Eco-Niwas Samhita, which were previously voluntary, but may become mandatory once notified by a state, Union Territory, or class of buildings. Also introduces provisions for a carbon credit trading scheme and mandatory minimum consumption of non-fossil energy sources.	<ul style="list-style-type: none"> • Provides the legal basis for making ECSBC and ENS compliance mandatory (once notified by a state/ULB) rather than voluntary, thereby determining whether the heat-resilient envelope and cooling-efficiency provisions in those codes are legally enforceable in a given city. • Relevant to ULBs considering whether to notify/adopt ECSBC or ENS locally, since this Act is the enabling instrument for making that adoption mandatory rather than advisory.



<p>National Disaster Management Authority (NDMA): National Framework for Heat Wave Mitigation and Management (2019, updated 2024); NDMA Cool Roof Handbook; NDMA Guidelines for Cooling Centres</p>	<p>National framework guiding State and District Disaster Management Authorities in preparing city- and state-level Heat Action Plans (HAPs). Heatwave is notified as a state-specific disaster under the Disaster Management Act, 2005, enabling access to State Disaster Response Fund (SDRF) financing for mitigation measures. More than 200 HAPs have been prepared across 23+ heat-prone states as of 2025.</p>	<ul style="list-style-type: none"> • Building-level guidance on cool roofs, roof insulation, and the shading of windows, external walls, and roofs. • Guidance on building orientation and to identify naturally cooler rooms within a building (e.g. north-facing rooms for use as cooling rooms). • Minimum operable window area (approximately 10% of floor area) and cross-ventilation guidance for designated cooling centres. • Recommends avoiding unshaded RCC walls and fully glazed facades in vulnerable building typologies such as informal housing and public cooling centres. • Provides ULBs with a route to access SDRF funding for heat-resilience retrofits, such as city-wide cool-roof programmes. • Verify the latest edition and any state-specific HAP addenda directly on ndma.gov.in before citing thresholds or figures in a published guideline.
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5.2 | Heat Action Planning for Heat-Resilient Cities

Heat Action Plans (HAPs) include a comprehensive assessment of heat risks across the most vulnerable population groups, including outdoor workers, women, children, the elderly, differently abled persons, people with chronic illnesses, low-income communities, and those living in rented residences. They offer a tailored, scientifically robust approach to guide officials in developing, implementing, and monitoring heat resilience action at the city level.

A HAP is prepared by integrating local climate trends and forecasts, ward-level heat risk assessments and urban heat island hotspot identification, city priorities and local context, and sector-specific goals, strategies, and interventions. It also sets out the institutional, governance, financing, and monitoring mechanisms required to coordinate implementation, track progress, and periodically revise the plan, alongside communication and advocacy measures to disseminate the city's heat action efforts and inform policymaking to strengthen urban heat resilience. Within this broader approach, the plan helps identify specific locations to implement passive and active building retrofits, such as commercial and residential areas, industrial zones, or government buildings.

Without this ward-level prioritisation, retrofit programmes and code enforcement are likely to spread uniformly across a city instead of focusing first on the areas and populations, including the vulnerable groups named above, that face the greatest heat risk. These are the locations where the heat resilience strategies presented in this guidebook, such as passive design, material choices, active cooling, and nature-based solutions, are needed most.

5.2.1 ICLEI South Asia's Heat Action Plan Toolkit

The ICLEI South Asia Heat Action Plan (HAP) Toolkit is a methodology that helps cities develop a city-scale HAP and systematically assess, plan, finance, implement, and monitor actions addressing urban heat risk. The toolkit follows a nine-step process, beginning with securing political commitment for developing a HAP and setting up coordination and stakeholder engagement structures. The process then assesses the city's socio-economic, environmental, and institutional context, and develops detailed heat risk assessments using the IPCC's Hazard, Exposure and Vulnerability (HEV) framework. These assessments are used to develop ward-level heat risk maps that identify vulnerable locations, infrastructure, and population groups facing the highest heat risks.



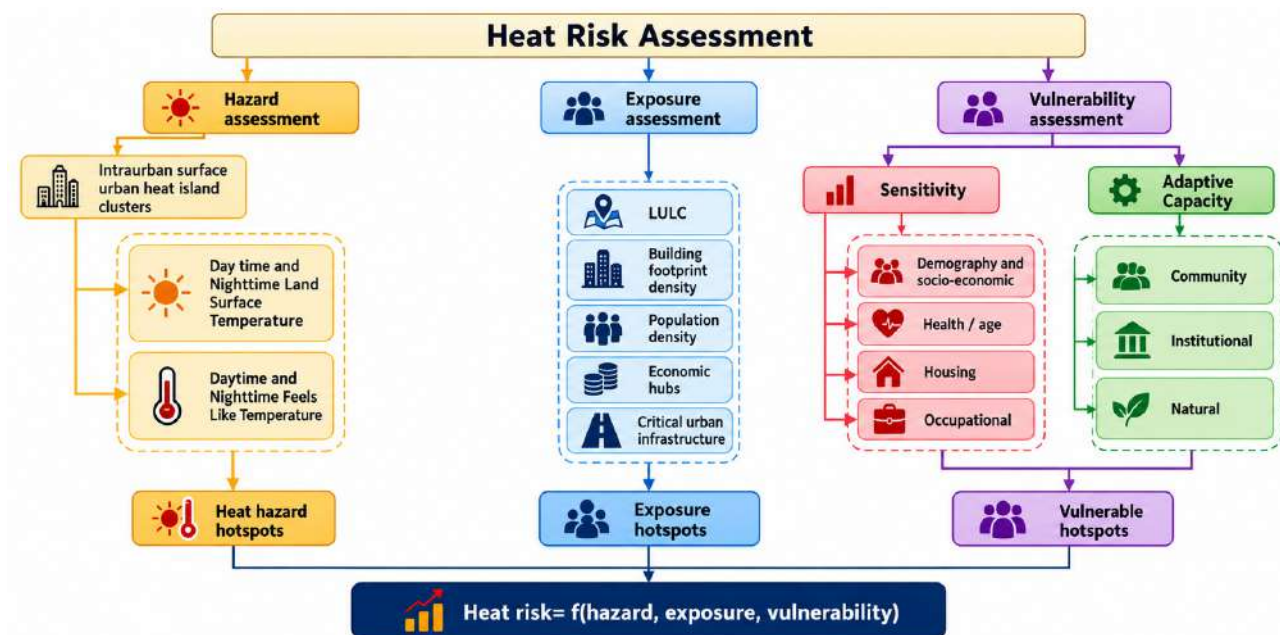


Figure 28: Ward-level heat risk assessment methodology (Source: ICLEI South Asia Heat Action Planning Toolkit)

5.2.2 From City-Scale to Building-Scale Action

Developing a city-scale HAP provides a strong foundation for both heat-resilient urban planning and passive and active cooling building retrofits. Ward-level heat risk assessment helps city officials and urban planners identify high heat hotspots and prioritise interventions such as urban greening, reflective pavements, green corridors, pocket parks, waterbody restoration, shaded public spaces, cooling shelters, and climate-sensitive land-use planning. By linking heat risk with remote sensing indices such as the Normalised Difference Vegetation Index (NDVI), which assesses the presence of healthy vegetation, and the Normalised Difference Water Index (NDWI), which assesses the presence of surface water, the HAP toolkit provides a framework for integrating heat resilience into master plans, development plans, infrastructure investments, and public space design.

The HAP also helps identify buildings in high heat risk wards that can be prioritised for retrofit measures to improve occupant thermal comfort and reduce cooling energy demand.

Examples include cool roofs, reflective building materials, green roofs, improved shading, energy-efficient cooling systems, and climate-responsive building design. By identifying vulnerable neighbourhoods, housing typologies, and high-risk populations, the HAP can direct targeted retrofit programmes to locations where they can have the greatest impact, such as low-income communities, informal settlements, public buildings, schools, and healthcare facilities.

5.3 | Bringing Codes, Standards, and Heat Action Plans Together

ICLEI's HAP toolkit brings together urban greening, urban planning, building retrofits, waterbody restoration, and early warning systems, with finance, institutional coordination, policy strengthening, and capacity building, to enable sustained action.



For ULBs, the most effective approach is to treat building codes and standards and HAPs as complementary rather than alternative instruments. Codes and standards, once notified, apply uniformly to set a minimum performance floor for every new or significantly renovated building in a jurisdiction. ***Heat action plans add what codes cannot provide: a ward-level, evidence-based view of where heat risk is most acute, which populations and building types are the most vulnerable, and therefore where limited public finance, retrofit incentives, and enforcement attention should be directed first.*** A ULB that adopts both mandatory codes to raise the baseline across all buildings, and a HAP to prioritise and finance targeted retrofits in its high-risk wards, is better positioned to convert the strategies in this guidebook into a sustained, city-wide reduction in heat risk than one relying on either instrument alone.



06 Case Studies: Heat Resilience in Practice

Singapore—City-Scale Microclimate-Sensitive Urban Planning



Singapore has nearly 50% green cover, ranging from nature reserves to parks and skyscraper greenery. Over 80% of households are within a 10-minute walk of a park. Since 2020, Singapore has planted about half a million trees to help mitigate urban heat.

Key heat-resilience initiatives:

- **Singapore Green Plan 2030:** Targets doubling the annual tree-planting rate (1 million more trees by 2030), implementing 200 ha of skyscraper greenery, and greening 80% of buildings (by gross floor area) by 2030.
- **Skyscraper Greenery Incentive Scheme:** The scheme funds up to 50% of rooftop or vertical greenery installation costs, capped at \$200 per square metre (sq. m) for rooftop greenery and \$500 per sq. m for vertical greenery on walls.
- **Microclimate considerations in building approvals:** Mandatory wind flow and shadow analysis for building development approvals (Urban Redevelopment Authority), making microclimate performance part of the planning approval process rather than relying solely on voluntary certification.
- **Research support:** Cooling Singapore, a multi-agency research-to-implementation programme (involving the National Research Foundation, Singapore-ETH Centre, Urban Redevelopment Authority, National Environment Agency, Building and Construction Authority, and the National Parks Board) is developing urban heat vulnerability maps and high-resolution microclimate models to inform policy through 2027.



Bengaluru—Infosys Campus



The Infosys campus buildings in Bengaluru demonstrate climate-responsive, energy-efficient institutional design.

Key heat-resilience features include:

- Optimised building orientation and controlled Window-to-Wall Ratio (WWR) to balance daylight access with solar heat gain.
- High-performance glazing combined with external shading devices; daylight-responsive architecture reduces reliance on artificial lighting.
- Reflective roofing materials and landscaped open spaces to reduce heat buildup across the campus.
- Energy-efficient HVAC systems paired with intelligent Building Management Systems (BMS) that continuously optimise lighting, cooling, and energy use.



Hyderabad—CII—Sohrabji Godrej Green Business Centre



Completed in 2003, the Confederation of Indian Industry–Sohrabji Godrej Green Business Centre in Hyderabad became the first LEED (Leadership in Energy and Environmental Design) Platinum-certified building outside the United States. The building later achieved net-zero energy status on its 15th anniversary.

Key heat-resilience features include:

- A circular footprint with internal courtyards captures and channels prevailing winds through the building.
- Two wind towers (windcatchers) draw warm air out from the top of the building. Incoming air is pre-cooled by passing over water pools and shaded planted areas, creating an evaporative cooling effect that reportedly lowers temperatures by up to 8°C.
- North-facing, double-glazed (argon-filled) façades admit diffused daylight to roughly 90% of interior spaces while limiting solar heat gain.
- Vegetated (green) roofs cover 55–60% of the roof area, adding insulation and reducing heat buildup; the remaining roof area hosts a 24-kW solar photovoltaic (PV) array.
- Aerated concrete block façades reduce air-conditioning load by an estimated 15–20% compared to conventional construction.
- The building achieves approximately 50% energy savings and a 35% reduction in water use compared to a conventional building of the same type.



New Delhi—Indira Paryavaran Bhawan



The Indira Paryavaran Bhawan in New Delhi is India's first on-site net-zero energy government building, housing the Ministry of Environment, Forest and Climate Change. It is rated GRIHA 5-Star (Green Rating for Integrated Habitat Assessment) and LEED Platinum.

Key heat-resilience features include:

- Two parallel blocks oriented north-south around a large central linear courtyard, creating a porous block form that channels airflow through the building and reduces solar exposure on major façades.
- Traditional jaalis, recessed windows, and deep overhangs reduce solar heat gain and glare while keeping interiors naturally cool without sacrificing daylight or views.
- Natural cross-ventilation through operable windows keeps corridors and much of the building naturally ventilated. Only about 38% of the built-up area (11,967 sq. m of 31,400 sq. m) is air-conditioned, while the remainder relies on passive design alone.
- Daylighting design allows natural light to reach roughly 75% of the office space, reducing the demand for artificial lighting.
- Geothermal heat rejection for HVAC cooling towers reduces both water use and cooling energy demand. A heat recovery wheel pre-cools incoming fresh air using exhaust air from toilets before it reaches the air-conditioned zones.
- The rooftop is entirely covered by a 930-kW solar PV array and the panels' overhanging edges double as shading devices, creating a cooler, shaded microclimate at roof level.
- Energy consumption is roughly 67% lower than the GRIHA benchmark, with on-site solar generation meeting the remaining demand to achieve net-zero status.





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