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Climate-Responsive Passive Design Strategies for Residential Buildings in Madhya Pradesh: A Thermal Comfort Perspective

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Abstract: Residential buildings in Madhya Pradesh experience substantial seasonal variation, including hot summers, monsoon humidity and cooler winter periods. These conditions make indoor thermal comfort a key consideration for sustainable housing. This review synthesizes literature on climate-responsive architecture, passive cooling, adaptive thermal comfort and Indian residential building guidance to identify strategies relevant to the state. The principal measures considered are building orientation, external shading, roof and wall heat-gain control, thermal mass, cross-ventilation, night purging, courtyards, vegetation and climate-appropriate materials. Evidence from Indian case studies indicates that envelope design and coordinated combinations of passive measures can reduce heat gains, while ventilation effectiveness depends on outdoor conditions and occupant operation. The review also highlights a limitation in the evidence base: published thermal-comfort studies are unevenly distributed across Indian climate regions, and state-specific, season-long residential data for Madhya Pradesh remain an important need. A practical framework is proposed combining climate analysis, occupant surveys, indoor environmental monitoring and calibrated building simulation. Rather than assuming one universal solution for the entire state, the paper recommends location-specific design and evaluation using indoor operative temperature, adaptive comfort, overheating hours and cooling-energy demand. These measures can support more comfortable, resilient and energy-conscious residential development

Keywords: Passive design; thermal comfort; residential buildings; Madhya Pradesh; natural ventilation; building envelope; adaptive comfort.

I. INTRODUCTION

Residential buildings must maintain acceptable indoor thermal comfort while minimizing energy consumption and occupants' exposure to outdoor heat. Thermal comfort is influenced not only by air temperature but also by mean radiant temperature, air velocity, relative humidity, clothing insulation, metabolic activity, and occupants' thermal expectations. As dependence on mechanical cooling increases, integrating passive design strategies at the planning and design stages becomes essential for reducing unwanted heat gains and improving indoor environmental conditions.

India's climatic diversity requires region-specific building design approaches rather than the uniform application of passive strategies. Previous studies on climate-responsive buildings in India have highlighted the importance of building-envelope characteristics, solar shading, natural ventilation, and integrated passive design measures in regulating indoor thermal conditions [1]. Reviews of thermal-comfort research in India have also identified geographical and methodological gaps, emphasizing that occupants in naturally ventilated buildings may adapt to a wider range of indoor temperatures than conventional fixed-temperature comfort models suggest [2,3].

Madhya Pradesh encompasses diverse climatic conditions, settlement patterns, urban densities, and residential construction practices. These variations can influence solar heat gain, indoor temperature fluctuations, ventilation potential, and occupants' thermal perceptions. Consequently, passive design strategies should be evaluated in relation to local climatic conditions, building characteristics, and patterns of residential occupancy rather than prescribed as a single standardized package for the entire state.

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This review examines the principal climate-responsive passive design strategies relevant to residential buildings in Madhya Pradesh, focusing on their underlying thermal mechanisms, potential contributions to indoor comfort, and implications for reducing cooling-energy demand. It also identifies research gaps and outlines the need for climate-specific assessments that integrate building-envelope performance, solar control, natural ventilation, and adaptive thermal comfort. Such an approach can support the development of context-sensitive residential design recommendations for improving thermal comfort and energy efficiency across the state.

II. REVIEW APPROACH AND SCOPE

This is a focused narrative review of peer-reviewed research on passive cooling, Indian residential thermal comfort, climate-responsive buildings and relevant building-energy guidance. The sources include review papers, field studies, building-performance evaluations and Indian code documents. The synthesis is qualitative: it does not claim a systematic database search, meta-analysis or measured performance results for Madhya Pradesh. Strategies are discussed in terms of physical mechanism, design implications and conditions that may limit effectiveness.

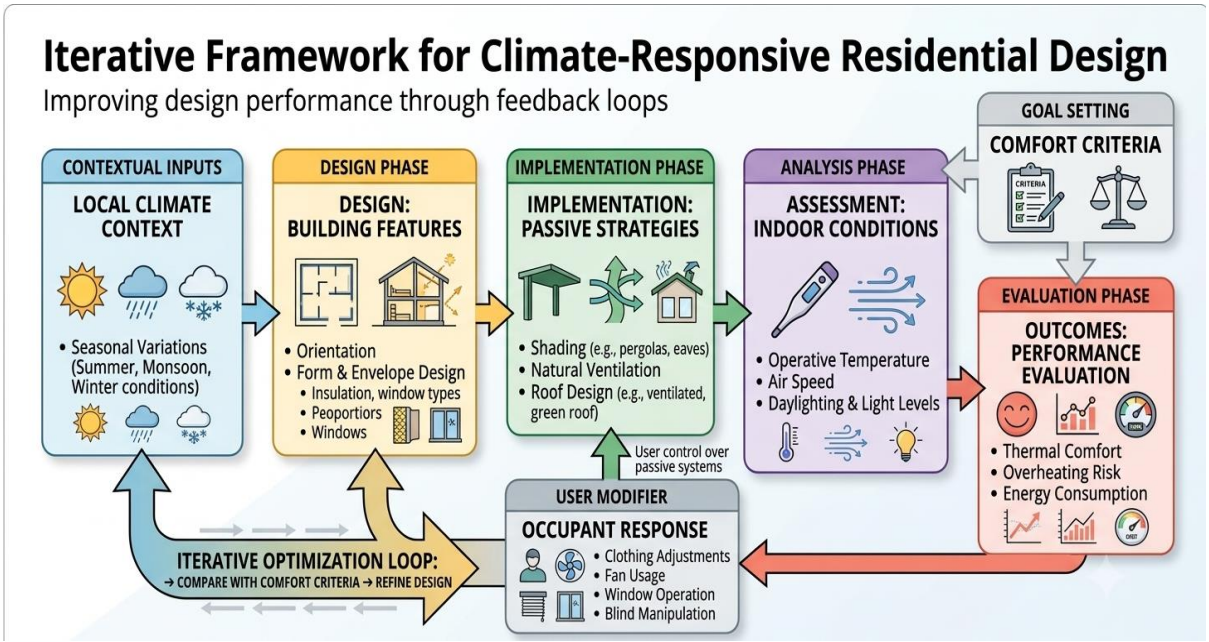


Figure 1. Conceptual framework linking climate, building design

III. THERMAL COMFORT AND CLIMATE-RESPONSIVE DESIGN

Thermal comfort is a subjective response to the combined thermal environment. Conventional heat-balance methods, such as PMV/PPD, are useful in controlled or mechanically conditioned settings, whereas adaptive models recognize that occupants in naturally ventilated buildings respond through clothing, window operation, fan use, activity and expectations. Indian research has highlighted the importance of locally relevant comfort assessment and occupant adaptation [2,3].

For a review of passive strategies, comfort should be evaluated alongside energy performance. Useful indicators include indoor operative temperature, hours outside an applicable adaptive comfort range, indoor-outdoor temperature difference, relative humidity, air speed, occupant thermal-sensation votes and cooling-energy use. A strategy that lowers indoor air temperature may not always improve comfort if humidity, radiant temperature or air movement remains unfavourable.

IV. PASSIVE DESIGN STRATEGIES FOR RESIDENTIAL BUILDINGS

4.1 Building orientation, form and spatial planning

Building form and orientation influence solar exposure, daylight, wind access and the area of envelope exposed to outdoor conditions. Compact forms can reduce exposed surface area, while room layout and window placement can

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support cross-ventilation. In practice, orientation should be evaluated together with plot constraints, neighbouring buildings, prevailing seasonal winds and the need to control low-angle east- and west-facing sun. A courtyard or shaded transitional space can provide a buffer between outdoor heat and occupied rooms, but its performance depends on proportions, shading, ventilation and local microclimate.

4.2 External shading and solar control

External shading prevents solar radiation from reaching glazing and opaque walls, where it would otherwise become heat. Overhangs, verandas, balconies, vertical fins, recessed windows and adjustable screens can be selected according to façade orientation. External shading is generally more effective at blocking solar gains than relying only on interior curtains. Designs should preserve useful daylight and allow winter sun where appropriate, while avoiding excessive obstruction of ventilation openings.

4.3 Roof and wall heat-gain control

Roofs are strongly exposed to solar radiation and deserve particular attention in low-rise housing. High-reflectance roof finishes, insulated or ventilated roof assemblies, shaded terraces and suitable ceiling cavities can reduce heat transfer to occupied rooms. Wall strategies include appropriate insulation, cavity construction, external shading and surface finishes that limit solar absorption. Indian building guidance for residential projects includes envelope heat-transfer requirements and provisions related to natural ventilation and daylight [4]. Actual performance depends on construction quality, ageing, dust, moisture and maintenance.

4.4 Thermal mass and time-lag

High-thermal-mass walls and floors can delay heat transfer and moderate short-term indoor temperature swings. However, thermal mass is not inherently beneficial in every situation: if stored heat cannot be released during cooler periods, it may prolong overheating. Its use should therefore be paired with an appropriate strategy for night ventilation or other heat rejection, where outdoor temperatures and air quality permit. Simulation or monitored evidence is needed to select wall thickness and material combinations for specific locations.

4.5 Natural ventilation and night-time heat rejection

Cross-ventilation can improve perceived comfort by increasing air speed and removing accumulated indoor heat. Effective airflow requires appropriately positioned inlet and outlet openings, unobstructed internal paths and attention to wind direction and surrounding obstructions. Night-time ventilation can cool building mass when outdoor air is cooler than indoor surfaces. However, windows should not be opened automatically when outdoor air is hotter, humid, polluted, noisy or insecure. Fans can complement natural ventilation by increasing air movement with relatively low electricity use.

4.6 Vegetation, courtyards and evaporative effects

Trees and planted areas can shade walls, roofs and outdoor surfaces and may reduce local radiant heat exposure. Shaded verandas and courtyards can improve the usability of semi-outdoor spaces. Evaporative cooling may be useful in suitably dry conditions, but its benefit decreases as humidity rises and it can increase water demand. Vegetation should be planned so that it does not block desired breezes or create persistent dampness in building fabric.

4.7 Climate-appropriate materials and traditional knowledge

Traditional architecture offers examples of shaded openings, courtyards, deep verandas, locally available materials and spatial arrangements adapted to local lifestyles. Research suggests that traditional passive techniques can inform contemporary housing, but they should be assessed against present-day density, household needs, construction practices and changing climate conditions [5]. Material selection should consider thermal properties, durability, embodied impacts, cost, availability and maintenance rather than relying on a single material label such as ‘traditional’ or ‘modern’.

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V. SYNTHESIS OF EVIDENCE AND DESIGN IMPLICATIONS

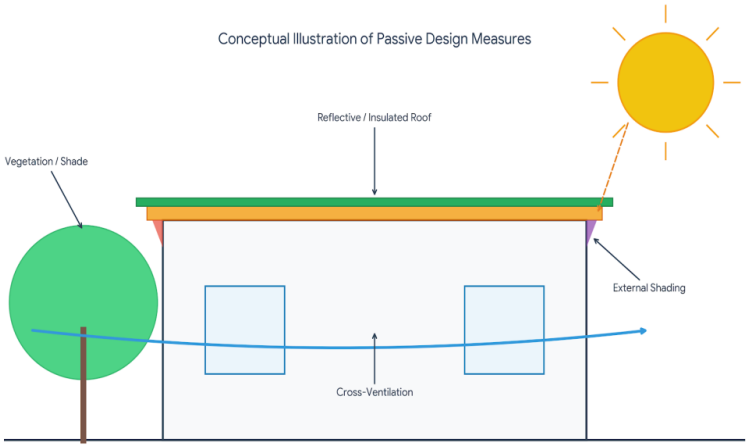


Figure 2. Conceptual schematic of selected passive design measures

Across the reviewed literature, no individual measure is consistently sufficient. A coordinated package—solar control, a roof and wall assembly suited to the local climate, effective ventilation when outdoor conditions allow, and occupant-accessible controls—is more defensible than a single-feature solution. Monitoring of Indian climate-responsive buildings has emphasized the importance of combining strategies and controlling unwanted heat transfer [1]. Reviews of Indian residential comfort similarly caution that comfort findings vary by climate, building type, occupant group and method [2,3].Table 1 and Table 2 represented the basic details suited for the design implications.

Table 1. Indicative Strategy Selection

Strategy	**Primary thermal mechanism**	**Key design caution**
External shading	Reduces direct solar gains	Coordinate with orientation and daylight
Cool/insulated roof	Reduces roof heat absorption and transfer	Check durability, glare and maintenance
Thermal mass	Delays and moderates heat flow	Needs a way to discharge stored heat
Cross-ventilation	Removes heat and increases air speed	Depends on wind, air quality and outdoor conditions
Night purging	Rejects stored heat during cooler hours	Avoid when nights remain hot or polluted
Trees/verandas/courtyards	Shade and improve microclimate	Do not obstruct airflow; consider water needs
Adaptive occupant controls	Allows behavioural adjustment	Provide safe, usable windows and fan controls

Table 2. Design criterion for Strategy Selection

Design measure	**Likely value in hot periods**	**Main condition / limitation**
External shading	High priority	Tune to façade orientation; retain daylight
Roof reflectance / insulation	High priority	Specify durable finishes and sound installation
Cross-ventilation	Conditional to high	Depends on wind, outdoor heat, humidity and air quality
Night ventilation	Conditional	Most useful when night air is cooler and clean
Thermal mass	Context-dependent	Pair with heat rejection to avoid stored heat
Trees and shaded outdoor spaces	Supportive	Allow airflow; consider water and maintenance

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VI. RESEARCH GAPS AND PROPOSED FRAMEWORK FOR MADHYA PRADESH

A clear research opportunity is the limited state-specific evidence linking residential design features with measured thermal comfort across seasons and locations in Madhya Pradesh. Existing Indian reviews identify uneven geographical coverage and the need for studies that represent different climates and residential contexts [6, 7]. The state-focused research agenda should therefore distinguish local climate, housing typology, construction materials, income and access to mechanical cooling.

A practical study could select representative urban and semi-urban locations and sample low-rise and multi-storey homes across summer, monsoon and winter. Indoor air temperature, relative humidity, globe temperature or operative temperature, air speed and outdoor weather should be logged at regular intervals. Occupants can complete short thermal-sensation, preference and acceptability surveys alongside records of fan use, window operation and air-conditioning. Building characteristics—orientation, window-to-wall ratio, shading, roof finish, wall construction and occupancy—should be documented [9-11].

Analysis should compare observed conditions with an appropriate adaptive comfort framework, report comfort and overheating hours, and examine the influence of design variables. Building-energy simulation can then test alternative packages such as roof improvements, shading, ventilation schedules and material changes. Models should be calibrated against measured data where feasible, and results should include uncertainty and sensitivity to weather files, occupancy and operating schedules. This approach would help separate plausible design recommendations from strategies demonstrated to work under local conditions. The approach is represented in Table 3.

Table 3. Suggested Monitoring and Evaluation Plan

Component	Suggested measure	Purpose
Indoor environment	Air/operative temperature, RH, air speed	Characterize thermal conditions
Outdoor conditions	Air temperature, RH, solar radiation, wind	Interpret seasonal and daily drivers
Occupant feedback	Thermal sensation, preference, fan/window use	Assess perceived comfort and adaptation
Building audit	Orientation, shading, roof/wall, openings	Link design features to outcomes
Analysis	Comfort/overheating hours; calibrated simulation	Compare strategies and test alternatives

VII. CONCLUSION

Climate-responsive passive design can support thermal comfort and reduce avoidable cooling demand in residential buildings of Madhya Pradesh, but strategies must be selected according to local weather, building form and occupant behaviour. Priority measures include external shading, roof and wall heat-gain control, effective ventilation, appropriately used thermal mass and shaded outdoor transitions. Adaptive comfort assessment and occupant feedback are important because indoor comfort is not determined by air temperature alone. The most significant next step is season-long field monitoring of representative homes in Madhya Pradesh, combined with calibrated simulation, to establish which design packages provide reliable comfort and energy benefits across the state.

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