

Assessment of climate-responsive bioclimatic design strategies to reduce carbon footprint in major indian cities

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Abstract

The building sector is a major contributor to global carbon emissions, particularly in rapidly urbanizing countries like India, where energy demand for cooling is increasing significantly. This study assesses appropriate bioclimatic design strategies to reduce the carbon footprint in the built environment across major Indian cities representing different climatic zones. Ten cities, such as Kolkata, Mumbai, Chennai, Jaipur, Jodhpur, Hyderabad, Delhi, Lucknow, Bengaluru, and Pune, were selected to cover hot-humid, hot-dry, composite, and tropical wet and dry climates. Climate data in EnergyPlus Weather (EPW) format were analyzed using Climate Consultant 6.0 to generate psychrometric charts and identify climate-responsive passive design strategies. The results reveal significant variation in thermal comfort conditions across climatic zones. Hot-humid cities show persistent discomfort due to high temperature and humidity, requiring shading, natural ventilation, and dehumidification strategies. Hot-dry cities demonstrate strong potential for passive cooling through thermal mass, night ventilation, and evaporative cooling. Composite climates require seasonally adaptive approaches



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integrating both cooling and heating strategies. In contrast, moderate climates such as Bengaluru and Pune exhibit a higher proportion of comfort h, where simple passive measures can effectively maintain indoor conditions. The study establishes that climate-specific bioclimatic design strategies can substantially reduce dependence on mechanical cooling systems, thereby lowering energy consumption and associated carbon emissions. By linking climatic analysis with design interventions, this research provides a comparative framework for prioritizing passive strategies across diverse urban contexts. The findings support the development of climate-responsive building guidelines and contribute to sustainable, low-carbon urban development in India.

Keywords: Bioclimatic design, carbon footprint, built environment, urban environment, climate change

INTRODUCTION

The building sector is one of the largest contributors to global greenhouse gas emissions^[1]. A significant portion of this emission originates from the energy used for cooling, heating, lighting, and ventilation in buildings^[1,2,3]. In rapidly developing countries like India, the demand for built space is increasing very fast due to urbanization, population growth, and economic expansion. Major cities such as Delhi, Mumbai, Kolkata, Chennai, and Bengaluru are expanding both horizontally and vertically^[3,4]. This rapid growth has led to higher energy use, especially for air-conditioning, which directly increases carbon emissions^[5,6]. At the same time, Indian cities are facing rising temperatures, urban heat island effects, and more frequent heat waves. These challenges make it necessary to rethink the way buildings are designed and operated.

Bioclimatic design offers a practical solution to reduce energy demand in buildings by using the local climate as a resource^[7,8,9]. Instead of depending heavily on mechanical cooling or heating systems, bioclimatic design focuses on building orientation, natural ventilation, shading devices, thermal mass, insulation, and landscape planning^[10,11,12]. In hot-humid cities like Kolkata and Chennai, strategies such as cross ventilation, shading, and reflective roofing can reduce indoor heat gain^[11,12]. In hot-dry cities such as Jaipur, thermal mass and courtyard planning can improve thermal comfort^[13]. In composite climates like Delhi, seasonal adaptability becomes important. Several international

studies have shown that climate-responsive design can reduce building energy consumption by 20-50 percent^[14,15,16,17]. Indian research has also explored passive cooling, cool roofs, green roofs, and energy-efficient envelopes^[10,11,12,13]. National building codes and rating systems, such as the Energy Conservation Building Code (ECBC), also encourage climate-sensitive design. However, the practical implementation across cities remains uneven.

Existing literature mostly focuses on single-city case studies or simulation-based assessments of individual buildings^[10,11,12,13]. Some studies evaluate energy savings, while others focus on thermal comfort or urban heat island mitigation^[9,11,12]. Some works discuss low-carbon materials and renewable energy integration^[14,15,16,17]. However, very few studies compare multiple major Indian cities representing different climatic zones in a single framework. Most research does not clearly link specific bioclimatic strategies with measurable carbon reduction outcomes at the urban scale. There is also limited integration of climatic diversity, urban density, and building typology in one systematic assessment. As a result, policy recommendations often remain general rather than climate-specific.

There is therefore a clear gap in developing a comparative and climate-responsive framework for major Indian cities. A structured assessment is needed to understand which bioclimatic strategies are most suitable for each climatic zone and how much carbon reduction can realistically be achieved. Without such a comparative approach, decision-makers may apply similar design guidelines across different cities, even though climatic conditions vary greatly. There is also a need to bridge the gap between theoretical potential and practical implementation.

The novelty of this research lies in its comparative, multi-city approach across major climatic regions of India. The study aims to evaluate and rank appropriate bioclimatic design strategies for selected major cities based on their climatic characteristics and potential carbon reduction impact. Instead of focusing only on energy savings, the research connects passive design strategies directly with carbon footprint reduction in the built environment. The study also intends to combine climate analysis, building energy assessment, and carbon estimation within one integrated framework. This

approach will help in generating city-specific design recommendations rather than general guidelines.

The central research question guiding this study is: which bioclimatic design strategies are most appropriate for reducing the carbon footprint of the built environment in major Indian cities representing different climatic zones? Additional questions include: how does climatic variation influence the effectiveness of passive design strategies; what is the estimated carbon reduction potential of selected strategies; and how can these strategies be prioritized for urban policy and planning?

The main objectives of this research are to analyze the climatic characteristics of selected major Indian cities; to identify suitable bioclimatic design strategies for each climate zone; to assess the potential reduction in building energy use and associated carbon emissions; to compare the effectiveness of strategies across cities; and to develop a climate-specific framework that can support low-carbon urban development in India. Through this approach, the study aims to contribute to sustainable building practices and climate-responsive urban planning in the Indian context.

APPLICATIONS OF BIOCLIMATIC DESIGN TO REDUCE THE CARBON FOOTPRINT

Bioclimatic design can be applied in buildings to reduce energy use and lower carbon emissions as discussed in Table 1^[18,19]. The main aim is to use natural climate conditions such as sunlight, wind, and temperature differences to maintain indoor comfort. When buildings depend less on air-conditioners, heaters, and artificial lighting, the overall energy demand decreases^[20,21]. Since most electricity in India is still generated from fossil fuels, lower energy use directly reduces the carbon footprint of the built environment.

One of the most important applications is proper building orientation. Buildings can be designed in such a way that they reduce direct heat gain from the sun, especially on east and west walls. Shading devices such as overhangs, louvers, balconies, and vertical fins can block unwanted solar radiation. In hot climates, reflective roofing materials and light-coloured exterior surfaces can further reduce heat absorption. These simple

measures help in lowering indoor temperature and reducing the need for mechanical cooling^[7,8,9].

Natural ventilation is another key application of bioclimatic design. Windows placed on opposite walls allow cross ventilation. Open courtyards and ventilated corridors improve air movement inside buildings. In hot-dry regions, night ventilation can cool down the building structure, which helps maintain comfort during the daytime^[22,23,24]. In moderate climates, controlled ventilation can maintain indoor comfort without air-conditioning for many months of the year. By improving airflow, buildings can reduce cooling energy demand significantly.

Thermal mass and insulation also play an important role. Thick walls, insulated roofs, and proper building envelopes can reduce unwanted heat gain in summer and heat loss in winter. In composite climates, buildings can be designed to capture sunlight in winter while blocking it in summer. This seasonal adaptation reduces both cooling and heating energy use^[23,24,25]. The use of local and low-carbon building materials further supports carbon reduction goals.

Landscape design is another practical application. Planting trees around buildings provides shade and reduces surrounding air temperature. Green roofs and green walls help in cooling the building surface. Water bodies and shaded open spaces improve the microclimate and reduce the urban heat island effect. These strategies improve outdoor comfort and reduce the cooling load of nearby buildings^[15,16,20,21,22].

Daylighting design also contributes to carbon reduction. Proper window size, skylights, and light shelves allow natural daylight to enter deep into interior spaces. When natural light is used effectively, the need for artificial lighting during daytime is reduced. This lowers electricity consumption and associated carbon emissions^[22-24].

In addition, bioclimatic design can be integrated with renewable energy systems such as rooftop solar panels. When passive strategies first reduce the energy demand, the remaining demand can be partly met through renewable sources^[24,25]. This combination creates a low-energy and low-carbon building system.

Overall, the application of bioclimatic design provides a practical and cost-effective way to reduce the carbon footprint in Indian cities^[21-24]. These strategies do not depend heavily on advanced technology. Instead, they rely on careful planning, climate understanding, and thoughtful design. When applied at the building and urban scale, bioclimatic principles can support sustainable development and long-term environmental protection.

Table 1. Bioclimatic Design Strategies for Reducing Carbon Footprint in the Built Environment^[9,17,18,19,20,21,24,25].

Bioclimatic Strategy	Design Application	Suitable Climate	Impact on Energy Use	Carbon Reduction Mechanism
Building Orientation	Align longer façade towards north-south direction	All climates	Reduces unwanted solar heat gain	Lowers cooling energy demand
Solar Shading Devices	Overhangs, louvers, fins, verandas, balconies	Hot-humid, composite, hot-dry	Blocks direct solar radiation	Reduces air-conditioning load
Reflective / Cool Roofs	High-albedo roofing materials	Hot-humid, hot-dry	Reduces roof surface temperature	Decreases indoor cooling requirement
Natural Cross Ventilation	Openings on opposite walls	Hot-humid, tropical wet & dry	Enhances airflow	Minimizes mechanical cooling
Stack Ventilation	Vent shafts, atrium spaces	Hot-humid, composite	Uses warm air rise principle	Reduces dependence on fans/AC
Thermal Mass	Thick walls, concrete, stone	Hot-dry, composite	Stores heat during day, releases at night	Stabilizes indoor temperature, lowers cooling load

	Opening					
Night Ventilation	windows at night in dry regions	Hot-dry		Removes stored heat		Cuts next-day cooling energy
Insulated Building Envelope	Insulated walls and roofs	Composite, cold regions		Reduces heat transfer		Reduces both heating and cooling energy
Courtyard Planning	Internal shaded courtyard	Hot-dry, composite		Improves microclimate		Reduces indoor temperature naturally
Green Roofs	Vegetation on rooftop	Hot-humid, urban areas		Reduces heat gain		Lowers cooling demand and urban heat island effect
Green Walls	Vertical vegetation	Urban hot climates		Cools wall surfaces		Decreases AC energy consumption
Landscape Shading	Tree plantation around buildings	All warm climates		Reduces surrounding air temperature		Indirectly lowers building cooling load
Daylighting Design	Skylights, light shelves, optimized window size	All climates		Reduces artificial lighting use		Lowers electricity consumption
Compact Building Form	Reduced exposed surface area	Hot-dry, composite		Minimizes heat exchange		Improves energy efficiency
Earth Air Tunnel	Underground air cooling system	Hot-dry		Pre-cools incoming air		Reduces the mechanical cooling need
Passive Solar Heating	South-facing glazing (controlled)	Composite, cold		Captures winter sunlight		Reduces heating energy use

Double Glazing	Energy-efficient windows	Composite, urban	Reduces heat gain and loss	Lowers HVAC energy demand
Low-Carbon Materials	Fly ash bricks, bamboo, local materials	All climates	Reduces embodied carbon	Cuts lifecycle carbon footprint
Roof Insulation with Ventilation Gap	Ventilated roof systems	Hot-humid	Prevents heat transfer	Reduces indoor heat build-up
Solar PV Rooftop Integration	solar panels	All cities	Generates renewable energy	Offsets grid-based carbon emissions

MATERIALS AND METHODS

Selection of the study areas

The selection of the study area [Figure 1] was carried out to represent the major climatic zones of India as defined by the India Meteorological Department (IMD) and broadly aligned with the Köppen climate classification. Since bioclimatic design strategies depend strongly on local climatic conditions, it was necessary to include cities that reflect diverse temperature patterns, humidity levels, rainfall distribution, and seasonal variations. The selected cities are also among the fastest-growing urban centers in India, with high building density and increasing energy demand^[9,10,17,18,19]. Therefore, they provide a suitable context to assess climate-responsive design strategies and their potential to reduce carbon emissions in the built environment.

Kolkata, Chennai, and Mumbai represent the hot-humid climatic zone. These cities are located in coastal or near-coastal regions and experience high temperatures combined with high relative humidity for most of the year. Cooling demand is very high due to discomfort caused by moisture-laden air and limited diurnal temperature variation. In such climates, natural ventilation, effective solar shading, reflective surfaces, and evaporative cooling techniques become important design responses. These cities were selected because they clearly demonstrate the challenges of reducing cooling energy consumption under hot and humid conditions^[26].

Jaipur, Jodhpur, and Hyderabad represent the hot-dry climatic zone. These cities experience very high summer temperatures but relatively low humidity. There is a large difference between day and night temperatures, especially in desert and semi-arid regions. In such climates, thermal mass, courtyard planning, compact urban form, and night ventilation are effective passive strategies^[27]. The inclusion of these cities allows the study to evaluate how traditional and modern passive cooling methods can reduce mechanical cooling loads and associated carbon emissions in arid and semi-arid urban environments.

The warm-temperate or composite climatic zone is represented by Delhi, Lucknow. These cities experience significant seasonal variation, with very hot summers, cool winters, and a short monsoon period. Because of this seasonal contrast, buildings require different strategies throughout the year. Passive solar gain in winter, shading in summer, and well-insulated building envelopes are essential in such climates^[28]. These cities were considered important for the study because they reflect the complexity of designing buildings that respond to both heating and cooling needs within the same year. The tropical wet and dry climatic zone is represented by Bengaluru and Pune. These cities experience moderate temperatures with seasonal rainfall and comparatively lower humidity than coastal cities. Although they have relatively comfortable climates, rapid urban growth and increasing air-conditioning use are raising energy demand. Mixed passive strategies such as controlled shading, natural ventilation, and optimized building orientation are suitable in these areas^[29]. The inclusion of these cities helps to understand how moderate climates can maintain low carbon footprints through preventive design approaches before energy demand becomes excessive.

Overall, the selected cities provide a balanced representation of India's major climatic regions and urban development patterns. By covering hot-humid, hot-dry, composite, and tropical wet and dry climates, the study ensures that the assessment of bioclimatic design strategies is comprehensive and climate-sensitive. This selection allows meaningful comparison across different environmental conditions and supports the development of city-specific recommendations for reducing the carbon footprint in the built environment.



Figure 1. Different cities selected for identifying the suitable bioclimatic design strategies to reduce the carbon footprint.

Identification of Appropriate Bioclimatic Design to Reduce the Carbon Footprint

In this study, appropriate bioclimatic design strategies were identified using Climate Consultant 6.0 software. Climate Consultant is a climate analysis tool that helps in understanding local weather conditions and suggesting suitable passive design strategies based on hourly climate data [Figure 2]^[12,30]. For each selected city, climate data files in EnergyPlus Weather (EPW) format were collected and used as input in the software. These files contain detailed hourly information on temperature, humidity, solar radiation, wind speed, and other important climatic parameters. The use of standardized EnergyPlus weather data ensures reliability and consistency in the analysis.

The climate data of each selected city were carefully examined in Climate Consultant 6.0. The software generated psychrometric charts, temperature distribution graphs, wind pattern analysis, and solar radiation profiles. Based on these outputs, the software suggested suitable passive design strategies such as natural ventilation, sun shading, thermal mass, evaporative cooling, passive solar heating, and improved insulation^[12,30]. The percentage of annual comfort h achievable through each strategy was also examined. This helped in understanding which design approach is more effective in a particular climate zone.

The suggested strategies were then screened and grouped according to their relevance to each climatic zone. For hot-humid cities, priority was given to shading devices, cross ventilation, reflective roofing, and reduction of internal heat gain. For hot-dry cities, thermal mass, night ventilation, and courtyard planning were emphasized. In composite climates, both summer cooling and winter heating strategies were considered. In tropical wet and dry climates, mixed passive approaches were evaluated. Only those strategies that showed strong potential to reduce cooling or heating demand were selected for further assessment of their carbon impact.

The identified bioclimatic strategies were linked to building energy performance by estimating their influence on reducing mechanical cooling and heating demand. Since operational energy use is directly related to carbon emissions, reducing energy demand through passive means leads to a lower carbon footprint. Therefore, the identification process focused on strategies that can reduce dependence on air-conditioning and artificial heating systems. This step formed the basis for further assessment of energy savings and carbon emission reduction in the selected cities.

Through this systematic approach, Climate Consultant 6.0 facilitated the selection of climate-responsive and location-specific bioclimatic design strategies. The use of EnergyPlus weather data improved the accuracy of the analysis. The method ensures that the selected strategies are not general recommendations but are scientifically supported by climatic data for each study area.

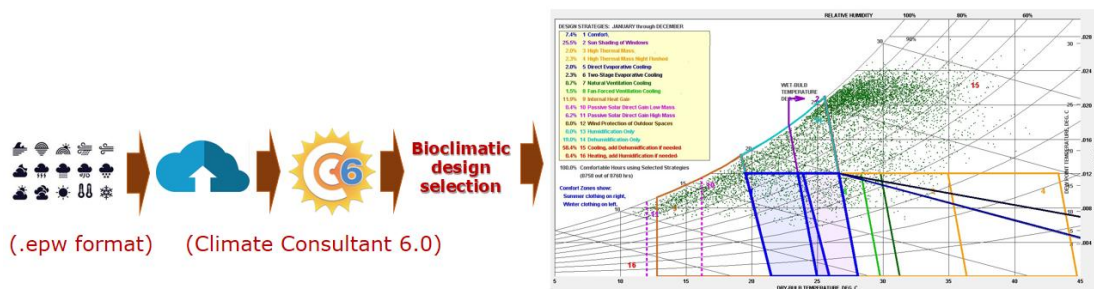


Figure 2. Identified the appropriate bioclimatic design using Climate Consultant 6.0 software.

RESULT

Climatic characteristics of selected cities

The analysis of Figure 3 shows clear seasonal and diurnal patterns of dry bulb temperature and relative humidity for the three hot-humid cities—Kolkata [Figure 3a,d], Mumbai [Figure 3b,e], and Chennai [Figure 3c,f]. In all three cities, dry bulb temperature remains high for most months of the year, with peak values observed during the late afternoon h (around 12 PM to 6 PM), especially from March to June. Early morning h (around 6 AM) show relatively lower temperatures, particularly during winter months. Among the cities, Kolkata exhibits slightly higher peak temperature values, followed by Chennai and Mumbai, although the overall pattern remains similar. In contrast, relative humidity is consistently high throughout the year, particularly in Mumbai and Chennai due to their strong coastal influence. Humidity levels are generally higher during early morning and late evening h, and remain elevated even during daytime in monsoon months. This combination of high temperature and high humidity indicates persistent thermal stress conditions, which significantly increases the need for effective passive cooling strategies in these urban environments.

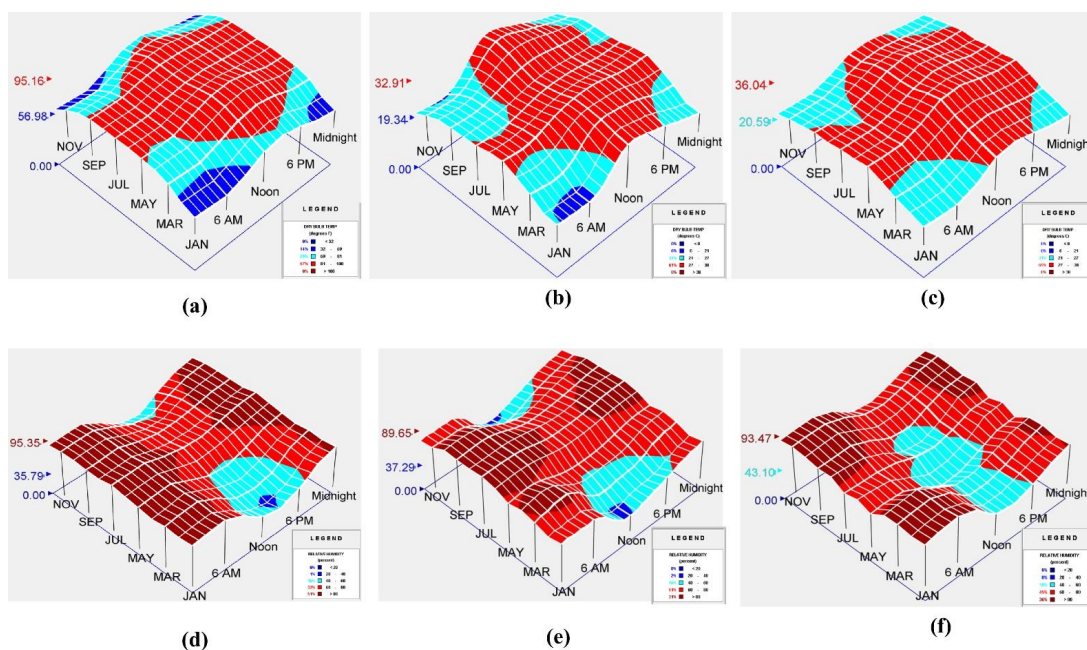


Figure 3. Dry bulb temperature (a) Kolkata; (b) Mumbai; (c) Chennai; and Relative humidity (d) Kolkata;(e) Mumbai; (f) Chennai.

The analysis of Figure 4 highlights distinct thermal and moisture patterns in the hot-dry cities of Jaipur [Figure 4a,d], Jodhpur [Figure 4b,e], and Hyderabad [Figure 3c,f]. The dry bulb temperature in Jaipur and Jodhpur shows very high values during the summer

months, particularly from April to June, with peak temperatures occurring in the afternoon h (around 12 PM to 6 PM). Hyderabad also experiences high temperatures, although slightly lower than the desert cities. A clear diurnal variation is observed, where early morning temperatures (around 6 AM) are significantly lower, especially during winter months. In contrast, relative humidity levels in Jaipur and Jodhpur remain low for most of the year, particularly during daytime, which is a characteristic feature of hot-dry climates. However, a slight increase in humidity is observed during the monsoon season. Hyderabad shows comparatively higher humidity than Jaipur and Jodhpur, especially during monsoon and evening h. The combination of high daytime temperatures and low humidity, along with cooler nights, indicates strong potential for passive cooling strategies such as night ventilation and thermal mass in these cities.

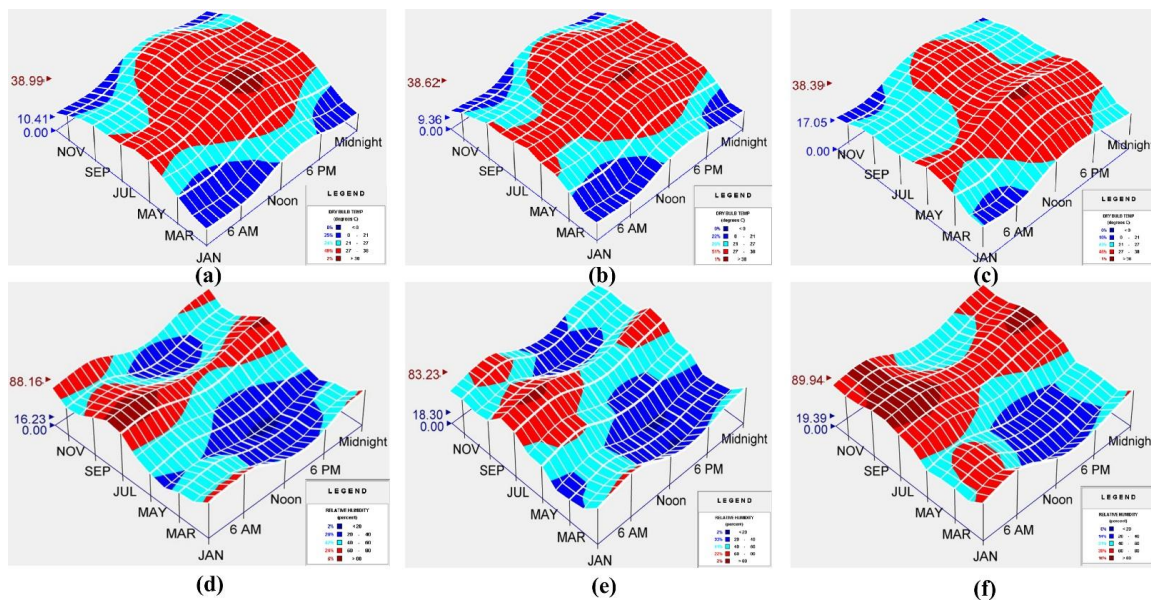


Figure 4. Dry bulb temperature (a) Jaipur; (b) Jodhpur; and (c) Hyderabad; and Relative humidity (d) Jaipur; (e) Jodhpur; (f) Hyderabad.

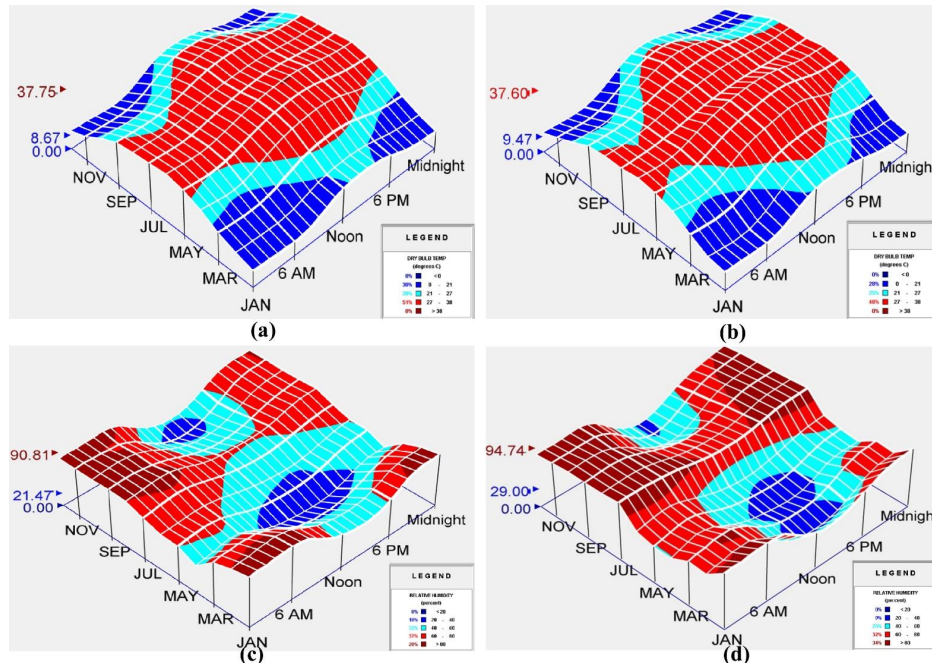


Figure 5. Dry bulb temperature (a) Delhi; (b) Lucknow; and Relative humidity (c) Delhi; (d) Lucknow.

The analysis of Figure 5 shows clear seasonal variation in both dry bulb temperature and relative humidity for the composite climate cities of Delhi [Figure 5a,c] and Lucknow [Figure 5b,d]. The dry bulb temperature remains very high during the summer months, particularly from April to June, with peak values observed in the afternoon h (around 12 PM to 6 PM). During winter months, especially from December to February, temperatures drop significantly, with the lowest values occurring in the early morning (around 6 AM). This indicates a wide annual temperature range. Relative humidity patterns also show strong seasonal variation. Humidity levels are moderate to high during the monsoon period (July to September), while relatively low values are observed during summer afternoons. In winter, humidity increases during morning and evening h. The combination of hot summers, cool winters, and seasonal humidity changes highlights the complexity of thermal conditions in composite climates, requiring flexible and seasonally adaptive bioclimatic design strategies.

The analysis of Figure 6 shows that Bengaluru [Figure 6a,c] and Pune [Figure 6b,d] experience relatively moderate climatic conditions compared to other cities. The dry bulb temperature remains within a comfortable range for most of the year, with only short periods of higher temperatures observed during the summer months, particularly

in the afternoon h. Peak temperatures are lower than those observed in hot-dry and composite climate cities, while early morning temperatures remain cool, especially during winter. In terms of relative humidity, both cities show moderate to high values, with slightly higher humidity during the monsoon season. Bengaluru exhibits relatively stable humidity throughout the year, whereas Pune shows more variation between dry and wet periods. The absence of extreme temperature conditions, along with moderate humidity levels, indicates a more comfortable climate, where passive design strategies such as natural ventilation, shading, and daylighting can effectively maintain indoor comfort with minimal dependence on mechanical cooling.

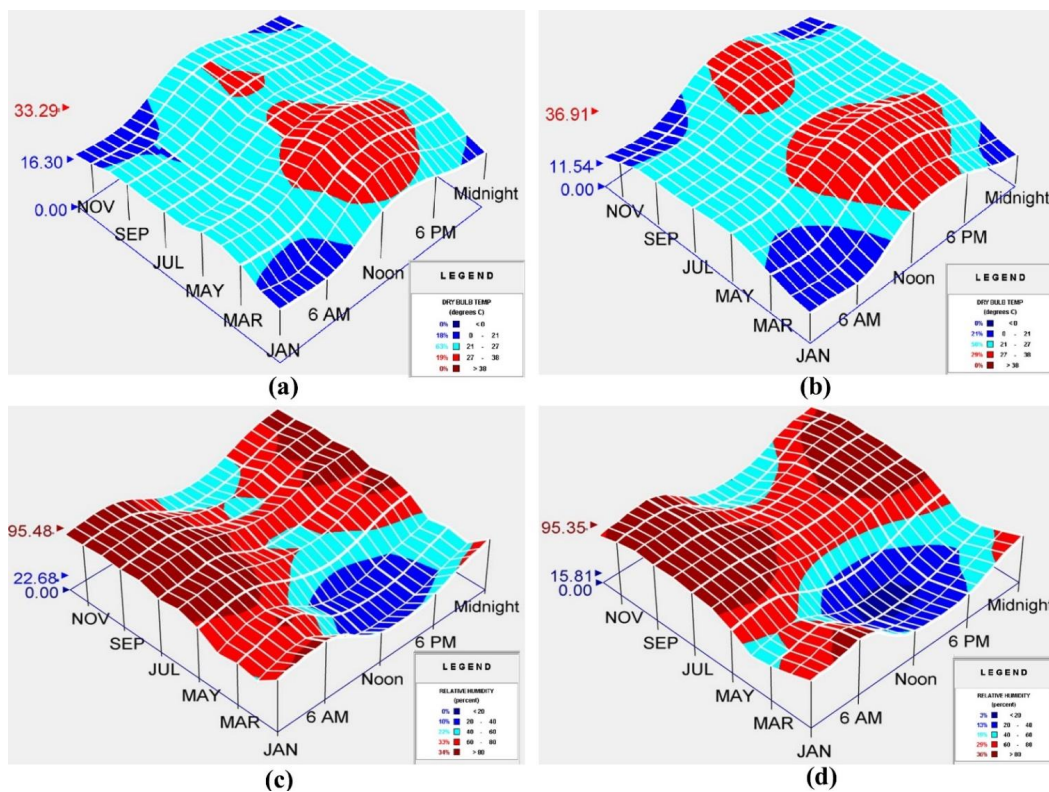


Figure 6. Dry bulb temperature (a) Bengaluru; (b) Pune; and Relative humidity (c) Bengaluru; (d) Pune.

Identified the appropriate bioclimatic design strategies

Figure 7a to 7c presents psychrometric analyses for three major Indian metropolitan cities Kolkata, Mumbai, and Chennai highlighting their distinct climatic characteristics and the corresponding suitability of bioclimatic design strategies. The distribution of hourly climatic data (green points) in all three figures indicates that a large proportion of the annual conditions fall outside the conventional thermal comfort zone, primarily due

to high temperature and humidity. However, the pattern and density of these distributions vary across cities, emphasizing the need for location-specific passive design responses. In Figure 7a, representing Kolkata, the data points show a relatively moderate spread with some proximity to the comfort zone boundary. This suggests that a significant number of h can be brought within comfort limits through passive interventions. Strategies such as solar shading, improved natural ventilation, and controlled air movement appear effective in shifting indoor conditions toward comfort. The presence of transitional climatic conditions indicates that Kolkata offers reasonable potential for bioclimatic optimization with minimal reliance on mechanical cooling. Figure 7b, corresponding to Mumbai, exhibits a dense clustering of points in the high temperature-high humidity region, reflecting its coastal and maritime climate. The limited overlap with the comfort zone highlights persistent thermal discomfort throughout much of the year. In this case, conventional passive strategies such as ventilation alone are less effective due to elevated humidity levels. The psychrometric chart suggests that enhanced air movement, dehumidification, and high-performance building envelopes are critical. Hybrid approaches combining passive and active systems may be necessary to achieve acceptable indoor comfort while still aiming to reduce energy consumption. In Figure 7c, representing Chennai, the data distribution shows both high temperature-humidity conditions and a wider seasonal variation compared to Mumbai. Although a large number of h lie outside the comfort zone, there is comparatively greater spread toward conditions that can be moderated through passive means. The chart indicates that a combination of strategies—including solar shading, evaporative cooling (during relatively drier periods), and thermal mass coupled with night ventilation—can effectively enhance comfort. This diversity of applicable strategies provides greater flexibility in bioclimatic design compared to the more consistently humid conditions of Mumbai. Overall, the comparative analysis of Kolkata, Mumbai, and Chennai underscores the critical role of psychrometric evaluation in guiding climate-responsive architectural design. While all three cities require interventions to mitigate heat and humidity, the intensity and combination of strategies differ. Tailoring bioclimatic approaches—such as shading, ventilation, thermal mass, and humidity control—to local climatic conditions can substantially reduce dependence on energy-intensive cooling systems, thereby contributing to lower carbon footprints in the built environment.

Figure 8a to 8c presents psychrometric evaluations for Jaipur, Jodhpur, and Hyderabad, representing hot-dry and composite climatic conditions in India. The distribution of hourly climatic data (green points) across these charts reveals that, unlike coastal cities, a significant proportion of conditions fall within or near zones that can be effectively modified using passive bioclimatic strategies. However, the intensity of thermal stress and the dominant design responses vary across the three locations. In Figure 8a, corresponding to Jaipur, the data points are widely distributed across high dry-bulb temperatures with relatively low humidity, characteristic of a hot-dry climate. A considerable portion of the data lies outside the comfort zone but within regions where passive strategies are highly effective. The psychrometric overlays indicate strong potential for interventions such as thermal mass with night ventilation, direct and indirect evaporative cooling, and effective solar shading. The diurnal temperature variation further enhances the feasibility of night flushing techniques, making Jaipur highly responsive to climate-sensitive architectural design aimed at minimizing mechanical cooling demand. Figure 8b, representing Jodhpur, exhibits an even more pronounced hot-dry profile, with data points concentrated at higher temperatures and lower humidity levels compared to Jaipur. This suggests more extreme thermal conditions; however, it also increases the effectiveness of evaporative cooling strategies. The chart highlights that a large fraction of uncomfortable h can be shifted toward comfort through passive downdraft evaporative cooling, high thermal mass, and compact urban form to reduce heat gain. Solar control through shading devices and optimized building orientation is critical in mitigating intense solar radiation. Thus, despite harsher conditions, Jodhpur offers strong potential for low-energy design solutions. In Figure 8c, representing Hyderabad, the climatic distribution reflects a composite climate with both hot-dry and warm-humid characteristics. The data points show a broader spread, including moderate humidity levels, which slightly reduces the efficiency of evaporative cooling compared to Jaipur and Jodhpur. However, a combination of strategies is applicable, including shading, natural ventilation, thermal mass, and selective evaporative cooling during drier periods. The overlap with multiple strategy zones indicates flexibility in design, where seasonally adaptive approaches can be employed to optimize indoor comfort conditions. Overall, the comparative analysis of Jaipur, Jodhpur, and Hyderabad demonstrates that hot-dry and composite climates in India are particularly suitable for passive bioclimatic interventions. Strategies such as thermal mass utilization, night ventilation, evaporative cooling, and solar shading can

significantly shift indoor conditions toward comfort. This reduces reliance on energy-intensive air-conditioning systems, thereby contributing to lower carbon emissions and enhanced sustainability in the built environment.

Figure 9a to 9b presents the psychrometric assessment of Delhi and Lucknow, both of which fall under the composite climatic zone of India, characterized by hot summers, cool winters, and a pronounced monsoon season. The distribution of hourly climatic data (green points) across both charts indicates substantial variability, with conditions spanning hot-dry, warm-humid, and mild periods. This wide spread highlights the seasonal complexity of these climates and underscores the importance of adaptive and flexible bioclimatic design strategies. In Figure 9a, representing Delhi, the data points show a broad dispersion extending from high-temperature, low-humidity regions (summer) to cooler conditions (winter). A significant proportion of the points lie outside the thermal comfort zone, particularly during peak summer months, indicating the need for effective cooling strategies. The psychrometric overlays suggest that thermal mass combined with night ventilation can play a crucial role in moderating indoor temperatures during hot-dry periods. Additionally, direct and indirect evaporative cooling is viable during dry conditions, while shading and solar control remain essential throughout the year. During the monsoon season, increased humidity reduces the effectiveness of evaporative cooling, necessitating enhanced ventilation and, in some cases, mechanical dehumidification. The presence of winter conditions also implies that passive solar heating and heat retention strategies can improve thermal comfort during colder months. Figure 9b, corresponding to Lucknow, exhibits a similar but slightly more humid profile compared to Delhi, particularly during the monsoon period. The clustering of data points indicates prolonged periods of thermal discomfort due to both heat and humidity. While many of the same strategies applicable to Delhi are relevant here, the effectiveness of evaporative cooling is somewhat limited by higher moisture content in the air. Consequently, greater emphasis is placed on shading, controlled ventilation, and building envelope optimization to reduce heat gain. Thermal mass remains beneficial, particularly when combined with night ventilation to exploit diurnal temperature variations. The overlap of multiple strategy zones suggests that a mixed-mode approach integrating passive and low-energy active systems—would be most effective in maintaining indoor comfort. Overall, the psychrometric analysis of Delhi and Lucknow demonstrates that composite climates demand seasonally responsive

design solutions. No single strategy is sufficient throughout the year; instead, a combination of passive techniques—such as shading, thermal mass, evaporative cooling (when feasible), natural ventilation, and passive solar heating—must be integrated. Such an approach can significantly reduce reliance on conventional HVAC systems, thereby lowering energy consumption and carbon emissions while enhancing indoor environmental quality in the built environment.

Figure 10a to 10b illustrates the psychrometric analysis for Bengaluru and Pune, two cities characterized by relatively moderate and composite climatic conditions compared to the more extreme climates of other Indian regions. The distribution of hourly climatic data (green points) in both figures shows a significant clustering around or near the thermal comfort zone, indicating a comparatively higher proportion of naturally comfortable hours throughout the year. This highlights the strong potential for passive bioclimatic design strategies to achieve indoor comfort with minimal reliance on mechanical systems. In Figure 10a, representing Bengaluru, the data points are concentrated within a narrow band of moderate temperature and humidity, reflecting its well-known equable climate due to elevation and vegetation cover. A noticeable portion of the data either falls within or lies very close to the comfort zone, suggesting that simple passive strategies can effectively maintain indoor comfort. The psychrometric overlays indicate that natural ventilation, air movement, and minimal shading are often sufficient to ensure thermal comfort. Thermal mass can also contribute to stabilizing indoor temperatures, although the relatively small diurnal variation reduces the need for intensive night ventilation strategies. Overall, Bengaluru demonstrates excellent suitability for low-energy and passive building design. Figure 10b, corresponding to Pune, shows a slightly broader distribution compared to Bengaluru, with some data points extending toward higher temperature regions, particularly during summer months. While a considerable portion of the climate remains within or near the comfort zone, there are periods of mild thermal stress that require intervention. The chart suggests that passive strategies such as solar shading, natural ventilation, and moderate thermal mass are effective in improving indoor conditions. During warmer periods, enhanced air movement becomes important, while the relatively lower humidity compared to coastal cities allows for limited use of evaporative cooling techniques. The seasonal variability, though not extreme, calls for adaptable design measures. Overall, the comparative analysis of Bengaluru and Pune indicates that these cities offer some of the most

favorable conditions for implementing bioclimatic design in India. The high percentage of comfort h and the effectiveness of simple passive strategies such as ventilation, shading, and thermal mass enable significant reductions in energy consumption. By optimizing building orientation, envelope design, and airflow, it is possible to minimize dependence on active cooling systems, thereby contributing to reduced carbon emissions and enhanced sustainability in the built environment.

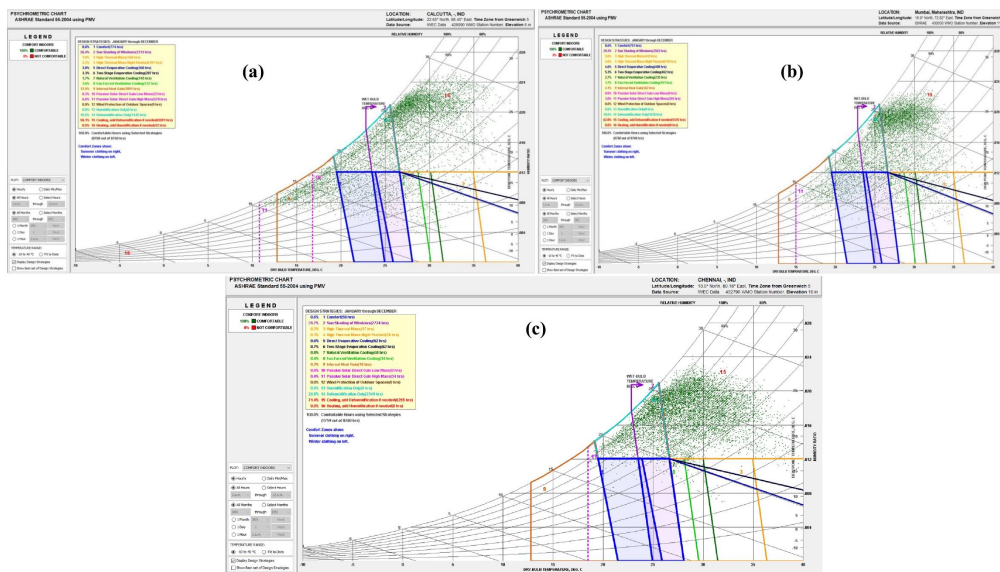


Figure 7. Identify the appropriate bioclimatic design strategies to reduce the carbon footprint (a) Kolkata; (b) Mumbai; (c) Chennai.

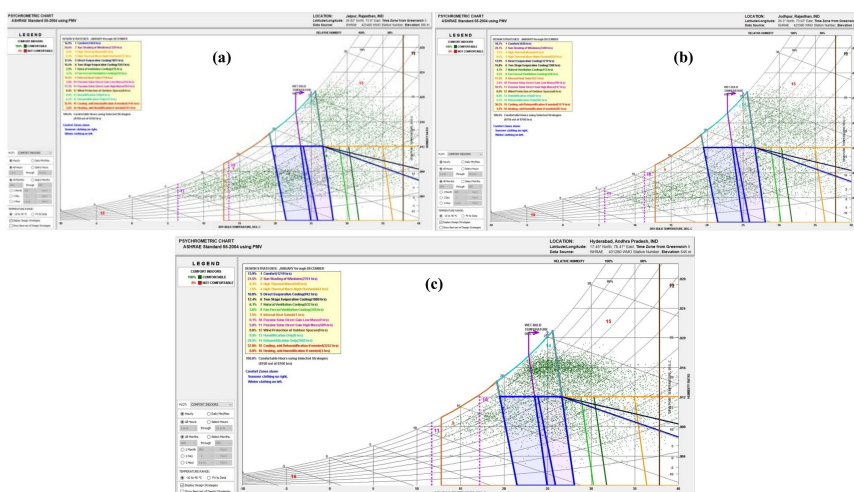


Figure 8. Identify the appropriate bioclimatic design strategies to reduce the carbon footprint (a) Jaipur; (b) Jodhpur; (c) Hyderabad.

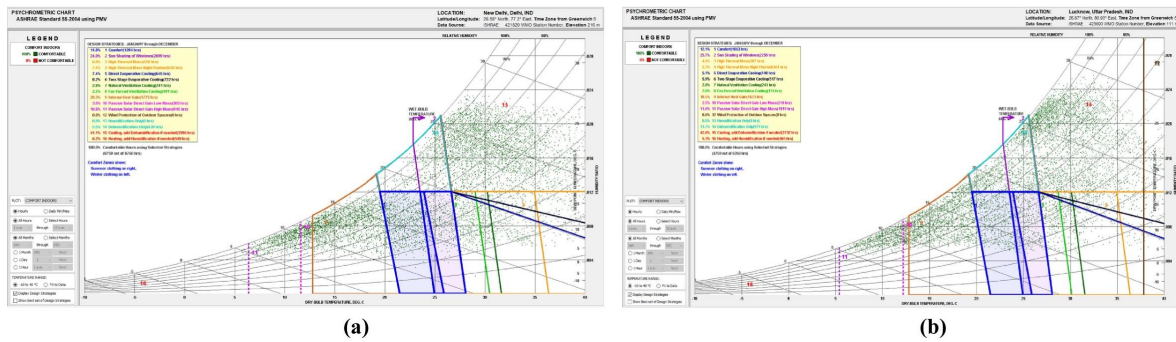


Figure 9. Identify the appropriate bioclimatic design strategies to reduce the carbon footprint (a) Delhi; (b) Lucknow.

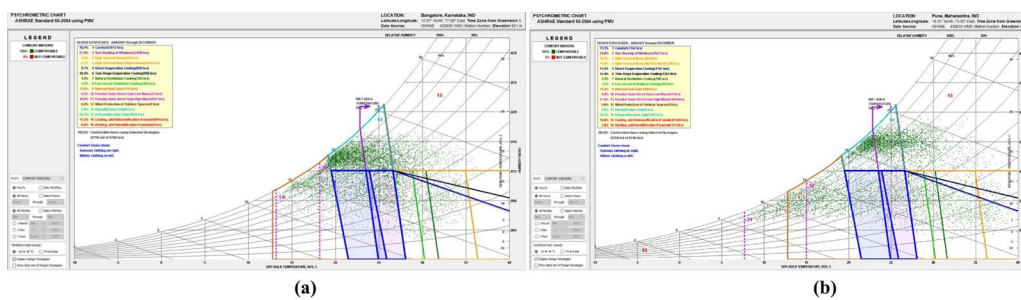


Figure 10. Identify the appropriate bioclimatic design strategies to reduce the carbon footprint (a) Bangalore; (b) Pune.

DISCUSSION

The present study demonstrates that the effectiveness of bioclimatic design strategies in India is strongly influenced by regional climatic conditions. Instead of applying a uniform design approach, the findings indicate that passive strategies must be selected according to local temperature, humidity, solar exposure, and seasonal variation. This supports earlier studies which emphasized that climate-responsive architecture is more effective when adapted to specific environmental conditions rather than relying on generalized building solutions^[9,14,15].

The analysis revealed that hot-humid cities such as Kolkata, Mumbai, and Chennai experience prolonged thermal discomfort because of the combined effect of high temperature and humidity. In these cities, natural ventilation, shading devices, reflective roofs, and reduction of solar heat gain emerged as the most suitable strategies. Similar observations were reported by Elaouzy and El Fadar^[20] who found that shading and ventilation are highly effective in improving building performance in warm and humid

climates. Studies on climate-responsive architecture also highlighted that controlling solar radiation and improving airflow can significantly lower indoor cooling demand^[10,12]. However, the present study further demonstrates that humidity remains a major limitation in coastal cities such as Mumbai, where ventilation alone may not ensure thermal comfort. Therefore, hybrid solutions integrating passive cooling with low-energy mechanical systems may be more practical in extremely humid urban environments.

In hot-dry cities such as Jaipur and Jodhpur, the study identified strong potential for passive cooling through thermal mass, night ventilation, courtyard planning, and evaporative cooling. These findings are consistent with earlier research which reported that large diurnal temperature variation in arid climates supports heat storage and night-time cooling strategies^[13,22,23]. The psychrometric analysis showed that a large proportion of uncomfortable h can be shifted toward comfort using passive interventions alone. This confirms the argument of previous studies that hot-dry climates offer some of the highest opportunities for low-energy building design^[14]. In addition, the current study highlights the importance of combining traditional architectural elements, such as courtyards and compact urban form, with modern climate-responsive materials to further reduce cooling energy demand and carbon emissions.

Composite climate cities such as Delhi and Lucknow showed greater seasonal complexity compared to other climatic zones. The study found that no single strategy is sufficient throughout the year, and buildings require seasonally adaptive solutions. Thermal mass, shading, natural ventilation, passive solar heating, and selective evaporative cooling all become important depending on the season. Earlier studies also emphasized the need for mixed-mode design approaches in composite climates^[24,28]. The present study supports these findings and further suggests that flexible building envelopes and adaptive ventilation systems are essential in cities experiencing both extreme summer heat and winter cooling requirements. This seasonal variability explains why energy demand in composite climate cities continues to rise despite improvements in building technology.

Among all selected cities, Bengaluru and Pune demonstrated the highest proportion of naturally comfortable h. Simple passive measures such as shading, natural ventilation, and daylight optimization were found sufficient to maintain indoor comfort for much of the year. Similar conclusions were reported in previous studies on climate-responsive residential design and energy-efficient buildings^[29,30]. The findings indicate that moderate climatic regions provide a valuable opportunity for preventive low-carbon urban development. If passive design principles are integrated at an early stage of urban expansion, these cities can avoid the future increase in cooling energy demand currently observed in many metropolitan regions.

The study also supports the growing understanding that bioclimatic design contributes not only to thermal comfort but also to carbon footprint reduction. Earlier research mainly focused on operational energy savings^[14,17], while the present study directly links passive design strategies with reduced dependence on mechanical cooling systems and lower greenhouse gas emissions. This relationship is particularly important in India, where electricity production still relies heavily on fossil fuels. Reducing cooling demand through climate-responsive design can therefore provide both environmental and economic benefits.

Another important contribution of this study is the comparative multi-city framework. Most previous studies concentrated on single buildings or single climatic regions^[12,13]. In contrast, the present research compares multiple major Indian cities within one integrated framework. This approach allows clearer identification of regional priorities and supports climate-specific urban planning. The findings suggest that national building guidelines should move beyond generalized recommendations and promote location-specific bioclimatic standards for different climatic zones.

The study also highlights the broader urban implications of passive design strategies. Landscape shading, green roofs, reflective surfaces, and urban vegetation can reduce the urban heat island effect while simultaneously improving outdoor thermal comfort. Similar observations were reported by studies on urban climate and heat stress mitigation^[15,16,20,21]. Integrating these strategies at the neighborhood and city scale can enhance urban resilience under future climate change conditions.

Overall, the discussion confirms that climate-responsive bioclimatic design has strong potential to reduce energy demand and carbon emissions in the Indian built environment. However, the effectiveness of each strategy varies considerably across climatic zones. Therefore, city-specific and climate-sensitive design frameworks are essential for achieving sustainable and low-carbon urban development in India.

CONCLUSION AND FUTURE PERSPECTIVE

This study highlights the importance of climate-responsive bioclimatic design as a practical pathway for reducing the carbon footprint of the built environment in India. The findings demonstrate that passive design strategies can significantly improve thermal performance and reduce dependence on energy-intensive cooling systems when they are properly adapted to local climatic conditions. Rather than relying on uniform building approaches, the research emphasizes the need for region-specific solutions that respond to variations in temperature, humidity, solar exposure, and seasonal patterns across Indian cities.

The study establishes that bioclimatic design should not be viewed only as an architectural concept, but as an integrated environmental strategy linking energy efficiency, thermal comfort, and carbon reduction. Passive measures such as shading, ventilation, thermal mass, daylight optimization, and landscape planning have the potential to support low-energy urban development while also improving indoor environmental quality. The research further indicates that moderate and composite climatic regions offer strong opportunities for preventive low-carbon planning if passive design principles are incorporated during the early stages of urban growth.

An important contribution of the study is the development of a comparative framework for evaluating climate-responsive strategies across multiple Indian climatic zones. This approach provides a stronger scientific basis for city-specific building guidelines and demonstrates that the effectiveness of passive design is highly dependent on local environmental conditions. The findings also suggest that integrating bioclimatic principles into urban planning can contribute to reducing urban heat stress, improving resilience to climate change, and supporting sustainable urbanization in rapidly growing cities.

Although the research provides valuable insights, further studies are required to strengthen practical implementation. Future work should integrate dynamic building energy simulations, lifecycle carbon assessment, and real-time field measurements to quantify the long-term environmental and economic benefits of bioclimatic design. Greater attention should also be given to occupant behavior, affordability, construction practices, and policy barriers that influence the adoption of passive strategies in the Indian context.

At the urban scale, future research can explore the combined role of urban morphology, green infrastructure, renewable energy integration, and smart technologies in improving climate resilience and reducing emissions. The development of climate-zone-specific design standards and stronger implementation of sustainable building regulations will also be essential for achieving long-term carbon reduction goals in India.

Overall, the study confirms that bioclimatic design has significant potential to support the transition toward low-carbon, energy-efficient, and climate-resilient cities. As urbanization and climate change continue to intensify, the integration of passive and climate-responsive design strategies into future building and planning practices will become increasingly important for sustainable development in India.

DECLARATIONS

Authors' contributions

Conceptualization, Methodology, Data Curation, Formal Analysis, Resources, Software, Visualisation, Validation, Investigation, Project Administration, Writing- Original Draft, and Writing - Review & Editing: Mahadev Bera;

Conceptualization, Methodology, Project Administration, Resources, Supervision, Writing - Review & Editing: Pranab Kumar Nag.

Availability of data and materials

The climate data used in this study were obtained from publicly available EnergyPlus Weather (EPW) files. The analyzed data generated through Climate Consultant 6.0 and other supporting materials related to the findings of this study are available from the corresponding author upon reasonable request.

AI and AI-assisted tools statement

Not applicable

Financial support and sponsorship

Not applicable

Conflicts of interest

The authors declared that there are no conflicts of interest

Ethical approval and consent to participate

Not applicable

Consent for publication

Not applicable

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