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Retrofitting strategies for low-rise apartment building envelopes during the summer: A literature review from the environmental context of New Delhi

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ABSTRACT

This paper reviews sustainable retrofitting strategies for low-rise apartment building envelopes in the composite climate of New Delhi, emphasising the need to reduce cooling energy use, improve indoor thermal comfort, and contribute to environmental sustainability through reduced carbon emissions. A systematic review of literature analysed several related studies, government reports, and policy documents from both national and international sources. It highlights envelope-related retrofit strategies, such as wall and roof insulation, reflective coatings, advanced glazing, and passive cooling methods. The review also covers simulation tools such as Design Builder and TRNSYS, as well as regulatory standards like the Residential Envelope Transmittance Value (RETV), used to assess retrofit effectiveness. The review highlights consistent evidence that envelope retrofitting can significantly reduce cooling energy demand while enhancing thermal comfort. It also identifies significant research gaps, including the limited availability of region-specific models for composite climates, underutilisation of RETV in design validation, insufficient integration of occupant behaviour, and inadequate attention to cost-effectiveness frameworks. The synthesis of existing literature provides valuable guidance for researchers, practitioners, and policymakers seeking to adopt envelope-focused retrofitting approaches. It highlights the importance of climate-responsive guidelines, simulation validation, and socioeconomic factors in future retrofitting efforts for India's residential sector. By consolidating dispersed findings into a structured framework, this review advances the body of knowledge on retrofitting strategies in composite climates. It offers a critical evaluation of current research, identifies unaddressed gaps, and suggests future directions for developing region-specific, cost-effective, and occupant-centred retrofitting models. Overall, it will demonstrate the connection between building performance improvements and environmental sustainability objectives, as well as climate-responsive design.

Keywords: environmental sustainability, thermal comfort, building envelope, retrofitting strategies, composite climate, RETV

INTRODUCTION

One of the main factors that contributes to the rising dependence on air conditioning in urban regions such as Delhi is the escalating influence of climate change, characterised by increasingly severe summer temperatures, which intensify the demand for thermal comfort. These climatic challenges are significantly impacting everyday life and prompting the execution of sustainable strategies intended to enhance indoor thermal comfort (Petidis et al., 2018). In this context, the building envelope plays a vital role in changing thermal performance. The main function of the building envelope is to serve as the boundary between indoor conditioned spaces and the external environment; it acts as the key barrier against climatic variables, protecting and regulating internal environmental conditions (Ghazwani et al., 2025). In addition to enhancing energy performance, retrofitting strategies can greatly reduce environmental impacts, such as greenhouse gas emissions and urban heat island effects, thereby aligning with global sustainability agendas (William et al., 2021). It must be capable of ensuring occupant comfort while minimising energy use. This review focuses on exploring sustainable retrofitting strategies applied to building envelopes in response to Delhi's composite climate, as shown in Figure 1 (Shandilya & Streicher, 2017). The study emphasises the performance of key envelope components, i.e. walls, roofs, and fenestration, with their role in enhancing thermal comfort and energy efficiency through targeted interventions (Ge et al., 2021). By doing so, it highlights the potential of envelope retrofitting as a critical pathway to achieving sustainable, low-energy residential buildings in India's evolving urban fabric (Berwal & Yadav, 2021)

Due to rising temperatures and increasing household incomes, the use of air conditioners has been growing rapidly in New Delhi. According to the International Energy Agency (IEA), the number of air conditioning units in India is projected to reach 240 million by 2030, a significant increase from 15 million in 2011 (Energy & IEA, 2021). According to the Directorate of Economics and Statistics (2012) and the National Sample Survey Organisation (NSSO), approximately 27.09% of households reside in buildings that are 10–20 years old, without any intervention of sustainable strategies, requiring retrofitting of their building envelope to reduce energy consumption. According to Shandilya et al. (2020), retrofitting has the potential to reduce energy demand in residential properties across India by 30% to 80%, depending on factors such as building age, climatic conditions, and the type of retrofit measures implemented.

Residential buildings are anticipated to be the fastest-growing segment within the building sector, thereby contributing to a substantial rise in electricity consumption. As illustrated in Figure 2, the residential and commercial sectors collectively account for 34% of India's total electricity usage, with the residential sector alone consuming approximately one-quarter of the country's overall electricity demand. It can be understood with the following studies by the government of India and NITI Aayog.

A 2016 study directed by the Centre for Science and Environment (CSE) revealed that the energy consumption of a 5-star-rated split air conditioner increases by an average of 20% when outdoor temperatures reach 45°C. The accompanying pie chart (Figure 3) shows the distribution of electricity use among various household appliances, with split ACs alone accounting for

Figure 1. Base case building showing the need for retrofitting in the Delhi climate

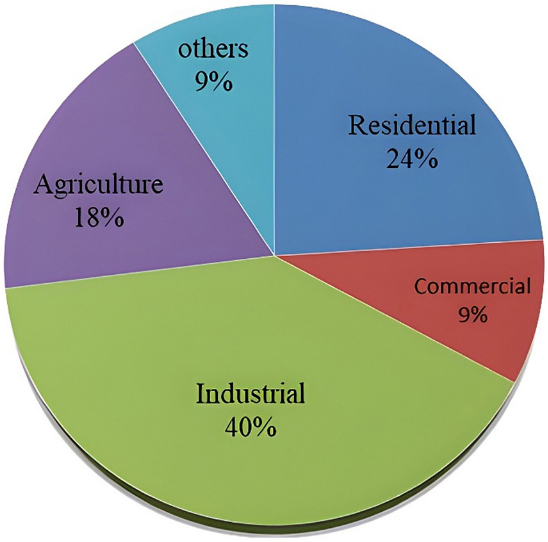

Figure 2. Consumption of electricity by sectors in India during 2017–18 (MOSPI)

a dominant 71% of total residential energy consumption (Delhi Electricity Board). This substantial share underscores the heavy reliance on air conditioning, particularly in climate-sensitive regions like New Delhi, which has a significant environmental impact. Other household appliances consume the remaining electricity. The chart (Figure 3) emphasises the critical need for energy-efficient retrofitting strategies.

This review was conducted by analysing over 30 national and international studies on building envelope retrofitting, with a focus on residential buildings in composite and hot climates. Many scholars and government agencies have studied the composite and hot-dry environment, with the majority of research focusing on improving the energy efficiency of residential structures. These studies also highlight environmental aspects such as life-cycle energy use, embodied carbon, and long-term ecological benefits of retrofitting measures. Most of the proposals discussed aimed to reduce electricity use in the building through various methods. Overall, most researchers aim to reduce energy consumption within buildings. The criteria for building thermal efficiency through envelope retrofitting in design and materials were among the findings. In contrast, others examined the bioclimatic characteristics of architectural design in relation to the local climate. Other researchers concentrate on energy-saving passive retrofitting solutions. Studies have shown that many parameters were investigated, including building sustainability, passive design, renewable technologies, façade treatment, energy-efficient elements, and cost optimisation. The building envelope was studied with limited parameters, focusing solely on wall and roof insulation. Some researchers used software simulations to identify

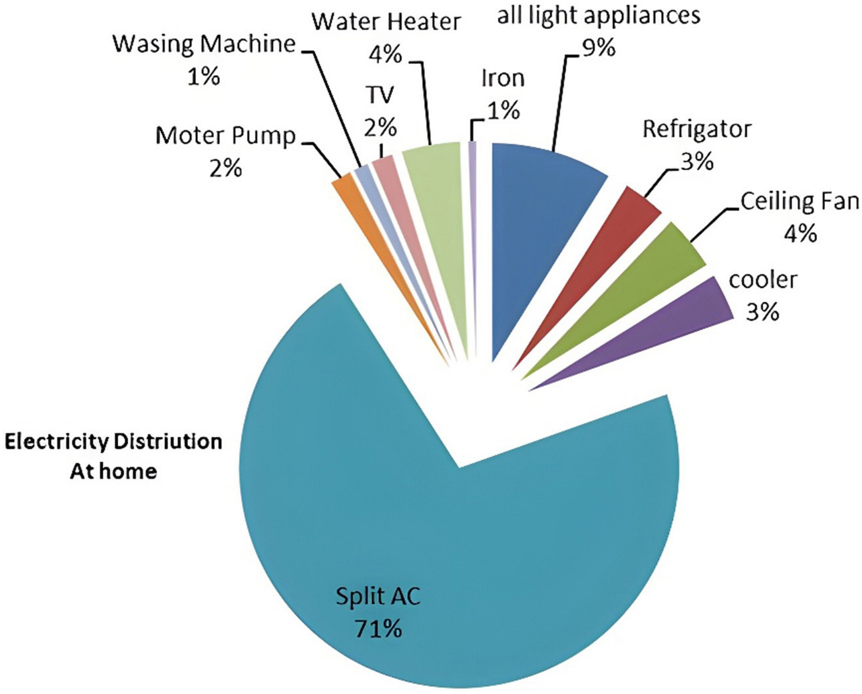

Figure 3. A chart showing more energy consumption by using AC's

building energy demands. Some functional previous related research studies are identified and mentioned in Tables 1-3. Here, Table 1 studies grouped by climate zone (composite, hot-humid, hot-arid, and temperate), Table 2 studies grouped by methodology (simulation-based, field measurement, survey, or mixed), and Table 3 studies grouped by building type (low-rise apartments, high-rise residential, and traditional houses).

Table 1 categorises previous studies based on the climatic settings where retrofitting strategies were tested. This arrangement illustrates how the success of retrofitting differs across hot-humid, hot-arid, temperate, Mediterranean, and mixed climates. By emphasising climate-specific results, the table shows that findings from other regions may not be directly applicable to New Delhi's hybrid climate, underscoring the importance of conducting region-specific research.

Table 2 displays studies categorised by their research methodology, including simulation-based analyses, field measurements, surveys, and mixed approaches. This comparison highlights how different methods affect the reliability and scope of retrofitting outcomes. It also shows that simulation tools (such as Design Builder, TRNSYS, and IES-VE) are predominant in the field. However, real-time validation through field experiments and occupant surveys remains underused.

Table 3 categorises the studies according to building types like low-rise apartments, high-rise residential structures, traditional homes, and institutional spaces. This classification facilitates comparison of results across various building forms, revealing that most research primarily focuses on standalone or traditional houses. There is relatively less emphasis on apartment buildings in mixed climate regions like New Delhi.

Envelope modification strategies (wall, roof, and glazing)

The important role of the building envelope is to transform the external environment and minimise the building's electric load and energy consumption, thus helping inhabitants to generate favourable internal conditions. One of the advantages of the building envelope is that it can control environmental variables such as daylight, heat, and air movement to contribute to comfort for residents while using minimal energy utilisation (El-Darwish and Gomaa, 2017). According to ASHRAE terminology, the building envelope comprises an outer element of a building, including walls, windows, doors, roofs, and floors. Basically, it is the physical boundary that divides the habitat spaces from the outside environment (Far & Far, 2019). Retrofitting measures applied to building envelope elements improve the energy performance of housing buildings in the proposed existing building in the research. Energy conservation procedures comprise the roof insulation, wall insulation, window components (area, glazing, and shading), and thermal mass (Alaidroos & Krarti, 2016)

Simulation and performance validation (e.g., Design Builder, TRNSYS)

Through simulation, we could investigate the impact of climate on retrofitting and can easily find the energy behaviour of the building and provide a solution accordingly through various simulation models (Nutakki et al., 2023). Energy simulation plays a crucial role in assessing a building's energy efficiency. During the energy simulation process, input of building design, building materials, residency of the building, internal gains, weather data, and other relevant information can be used to analyse indoor thermal conditions such as humidity, temperature, and heating and cooling load (Santy et al., 2017). Energy simulation and other assessment programmes are engaged to analyse various parameters, including thermal insulation, solar radiation, energy demand, thermal comfort, and air tightness. Depending on the analysis of previous conditions, various helpful strategies might be proposed to improve building envelope design (Homod et al., 2021)

Residential envelope transmittance value analysis

Residential envelope transmittance value (RETV) calculation is the net heat gain rate through the building envelope (excluding the roof) divided by the building envelope area (Figure 4). RETV analysis is a systematic approach to evaluating and ascertaining building thermal comfort (Wienerberger, 2018). It is used to assess the thermal efficiency of a building and to maximise the RETV value for a building. RETV analysis can help in designing buildings that are EE and provide thermal comfort to the occupants (Kuchangi, 2022).

Table 1. Previous studies grouped by climate zone

Author	Aim/work	Location/ Climate	Findings
(Ghazwani et al., 2025)	Environmental impacts of advanced building envelope materials for energy retrofitting	Hot climates are considered, but the review encompasses a range of climatic conditions.	Advanced envelope materials like PCMs, aerogels, VIPS, and reflective coatings enhance thermal comfort while reducing energy use and CO_2 emissions.
(Monné-Bailo et al., 2024)	To accurately assess energy savings from building energy rehabilitation (one retrofitted, one not)	Zaragoza, Spain/ semi-arid climate with hot summers	The retrofitted building achieved a 58.42% reduction in energy consumption compared to the non-retrofitted one.
(Nasir et al., 2023)	Analyse the energy efficiency of hotel façades by evaluating the annual cooling load through hourly simulation.	Penang, Malaysia/ Hot and humid tropical climate	Cooling energy consumption is 553 kWh/m² for conventional hotels and 538 kWh/m² for modern hotels. Modern façade designs with passive strategies like optimised WWR, improved glazing, and lighter wall colours demonstrate greater energy efficiency.
(Lozoya-Peral et al., 2023)	Identifying the best passive strategies to rehabilitate a traditional house, enhancing its energy efficiency and comfort.	Warm semi-arid Mediterranean climate	The implementation of thermal insulation, shading devices, and optimised window sizing can reduce energy consumption by up to 87%.
(Nutakki et al., 2023)	To evaluate the ageing properties of high SRI (cool) paints and estimate the energy savings they can provide when used in retrofitting residential buildings in hot desert climates.	GCC region (hot, arid/desert climate)	Cool paints, when applied to roofs, walls, and combined with window films, can achieve up to 34% annual energy savings. However, they experience SRI degradation of 36% on roofs and 25% on walls over three years. Energy savings vary between 31% and 44%, depending on the paint colour and application method.
(S, 2022)	To analyse the building's thermal efficiency through RETV analysis.	Composite climate	RETV analysis is applied in daily construction, resulting in approximately 20% savings in cooling energy and a reduction of 25 million kWh of electricity.
(Ciardiello et al., 2020)	Using multi-objective optimisation, lower building energy use and emissions.	Mediterranean climate.	A 60% annual energy demand reduction is achieved through geometry optimisation,
(Shandilya et al., 2020)	Evaluate retrofitting strategies for reduced energy demand	India/ All five types of climates	Insulated thermal envelopes can decrease the heating energy demand of a building by more than 70%. Insulated walls and roof + three pane Composite New Delhi
(Felimban et al., 2019)	Explore current user behaviour impacting energy consumption in residential buildings in Jeddah.	Jeddah/ hot and dry climate	Several factors influence energy performance, including the thermal properties of building materials and the requirement to maintain indoor temperatures below 24°C for thermal comfort.
(Tewari et al., 2019)	Develop Bio Climatic Design Charts for thermal conditions and passive cooling strategies.	Jaipur/Composite climate	Evaporatively cooled buildings were comfortable under different conditions than the ASHRAE 55 and ISO 7730 standards.
(Naveen Kishore & Rekha, 2018)	Assess how local climate affects building heating and cooling energy requirements using statistical methods.	Composite climate	Natural comfort ranged from 23% to 46%, passive cooling from 26.5% to 53.5%, and passive solar heating from 3% to 20%.
(Apeksha Shandilya & Dr Wolfgang Streicher, 2017)	Applying an integrated passive design strategy to lower heating and cooling needs in an existing building in New Delhi.	New Delhi/ composite climate	To enhance the building's thermal envelope, high-efficiency insulation materials like EPS, XPS, or glass wool were selected for external walls and roofs in place of standard windows.

Table 2. Previous studies grouped by methodology

Author	Aim/work	Methodology	Findings
(Berwal & Yadav, 2021)	Retrofit Strategy in an Existing Building under code	Survey and Simulation Method	Energy consumption reduction after applying the ECBC for existing buildings
(Ge et al., 2021)	Analysed optimisation strategies, packages of envelopes on existing residents' thermal comfort demands	Questionnaire surveys and field measurement with the IES-VE software as a simulation	Improving airtightness can reduce energy consumption by 9.6% to 46.7%. Enhancements to envelopes, interior walls, and floors contribute additional savings of 13.6%–37.3% and 6.0%–7.9%, respectively.
(Homod et al., 2021)	Impact of various building envelope materials on thermal comfort and energy savings from air conditioning.	Modelling in the MATLAB/Simulink environment and validated by a field experiment through ANSYS software output.	Vernacular buildings offer the greatest energy-saving potential, reaching up to 47.83% over a 24-hour period.
(Bataineh & Al Rabee, 2021)	Identify cost-optimal efficiency design strategies for building energy savings.	Design Builder software for energy usage, real-time field measurement data for model verification	Optimal design combinations can reduce annual electricity consumption by up to 50% at minimal cost, with a payback period of approximately 9.3 years.
(Mathur & Damle, 2021)	Measure an infiltration factor for an apartment to revise the Indian residential envelope transmittance value (RETV).	Simulation-based analysis and fieldwork measurement	It was observed that 1 ACH of infiltration results in 5.46, 4.22, and 3.53 W/m² of RETV in hot-dry, warm-humid, and cold-humid climates, respectively.
(Ijasahmed et al., 2019)	Retrofitting analysis of an existing building to transform it into an EE building	Simulation method (Revit)	The existing building's Energy Usage Intensity (EUI) is 193 kWh/m²/year. Using passive features alone reduces this to 138 kWh/m²/year.
(Jha & Bhattacharjee, 2018)	Providing an effective tool for retrofitting hot climate building envelopes to reduce the cooling load in existing buildings.	Case study method	Developing a user-friendly spreadsheet-based model for automatically selecting energy-efficient envelope retrofit solutions
(Petidis et al., 2018)	Identify suitable building interventions to improve energy performance.	Survey method	Combining thermal insulation, a green roof, LED lighting, and window replacement resulted in a 36% energy savings.
(Khambadkone & Jain, 2017)	Create a bioclimatic analysis tool to assess comfort potential.	Climate consultant software and case study method	The tool's findings can offer significant implications for architects in developing energy-efficient buildings.
(Kumar et al., 2017)	Thermal efficiency of buildings made of different materials in India's various climate zones	Design Builder	Reflective window glasses crafted from bronze, green, and bronze decrease heat gain in buildings by 2.52%, 3.83%, and 6.46%, respectively.
(Farjami & Mohamedali, 2017)	Explore the optimisation of passive solar design principles to reduce energy consumption.	Case study, survey, and simulation	Research emphasised the importance of considering passive parameters and material selection specifications for effective energy management.
(Kamel & Memar, 2016)	Study existing energy retrofit methods for the residential and commercial sectors.	BE modelling and analysis	Implementing wall insulation for better energy saving by 10.8%

Thermal comfort analysis

Another essential factor to investigate in the literature review is thermal comfort. Thermal comfort is defined as "the state of mind that expresses satisfaction within the thermal environment", according to ASHRAE 55 standard. It recommends a range of 23–26 °C for hot conditions in homes, and a relative humidity range of 30% to 60% indoors. Bureau of Energy Efficiency (BEE), India, suggests maintaining AC settings at 24–25 °C or higher for energy efficiency and comfort (Power, 2018). According to the National Building Code (2016), the indoor operative temperature range for comfort is 23.5 °C to 28 °C in non-air-conditioned buildings and 24–26.5 °C in AC zones. A study by Chaudhary (2020) clarified on adaptive comfort standards, as it is hard to have a thermal comfort

Table 3. Previous studies grouped by building type

Author	Aim/work	Building/ Space	Findings
(Almasri & Alshitawi, 2022)	Reviewing energy efficiency in residential buildings in GCC countries, with the electricity usage	Residential building	Increasing AC efficiency and wall thermal insulation as BER causes a reduction in electricity consumption between 10 and 30%
(Xu et al., 2021)	Analyses existing retrofitting methods for existing residences	Typical residential buildings built between 1980 and 2000	Multiple performance-based retrofitting strategies (BER) of the existing residential envelope system with low energy consumption
(Mushtaha et al., 2021)	Explore and enhance thermal performance in Gaza's buildings by minimising high energy consumption with passive strategies.	Residential buildings	Passive design (shading devices, ventilation, and insulation) reduces building energy use by 9.89 kW, or 59% of total consumption.
(He et al., 2021)	Identifying effective and sustainable retrofit solutions for existing buildings	High-rise Residential building	Different climatic conditions demand varying thicknesses of external wall insulation to efficiently manage energy use for heating and cooling.
(Saikia et al., 2020)	Optimise thermal retrofits in a building envelope for improved energy performance,	Residential building.	Improved envelope design achieves up to 33.5% heat gain reduction and 9.2 kWh/day electricity savings.
(Biju & Ayyathurai, 2019)	Simulating and optimising building designs at the early design stage	Two-storey residential building	The optimal orientations for energy savings in a composite climate have been identified as east (E) and northeast (NE), offering the most favourable conditions for reducing energy consumption.
(Sachar Sneha et al., 2018)	Establishing the relation of AC with indoor thermal comfort in terms of the climate.	Residential Building (the largest RAC user group in India)	RAC usage patterns, linkages between thermal comfort preferences and factors like climate, seasonality, set-points, and SHG.
(Jeong et al., 2017)	Identify possible issues in the current Building Energy Consumption for the existing setup building.	Multi-family housing complexes	Providing a more accurate assessment of energy performance
(Fan & Xia, 2017)	Develop a multi-objective optimisation model for retrofitting building envelopes to improve energy efficiency.	Existing residential building	Retrofitting windows, external walls, and roofs and integrating rooftop solar panels can help reduce energy consumption.
(Arab et al., 2017)	To analyse and compare the thermal surface temperatures of two high-rise residential apartments	High-rise residential apartments	Passive shading devices were moderately used to reduce heat gains, and while passive design strategies were present, they were not fully optimised for solar radiation control.
(Alaidroos & Krarti, 2016)	Assess how well passive cooling strategies decrease thermal cooling loads and air conditioning energy use in residential buildings across the Kingdom of Saudi Arabia (KSA).	Residential villas with an improved building envelope	Natural ventilation and evaporative cooling significantly reduce cooling energy use and electrical peak demand by 22%

for Delhi due to the composite climate (hot summer, cold winter, and wet monsoon). So, adaptive thermal comfort is 22 ºC to 28 ºC.

The field case study-based model

Many researchers have worked on the base case model in relation to various applied retrofitting strategies to justify the changes in energy savings from the earlier stage. It is referred to as the pre-retrofitting and post-retrofitting impact. Monné-Bailo et al. (2024) show that a non-retrofitted building served as the base case, directly compared with an identical but rehabilitated building. Its retrofit upgrade shows an annual energy saving of 58.42%. Lozoya-Peral et al. (2023) used the existing traditional house as the base case, assessing its performance under current conditions. Shandilya et al. (2020) use a typical Indian single-family residential building as a base case model, simulated in its original (non-retrofitted) condition for five Indian

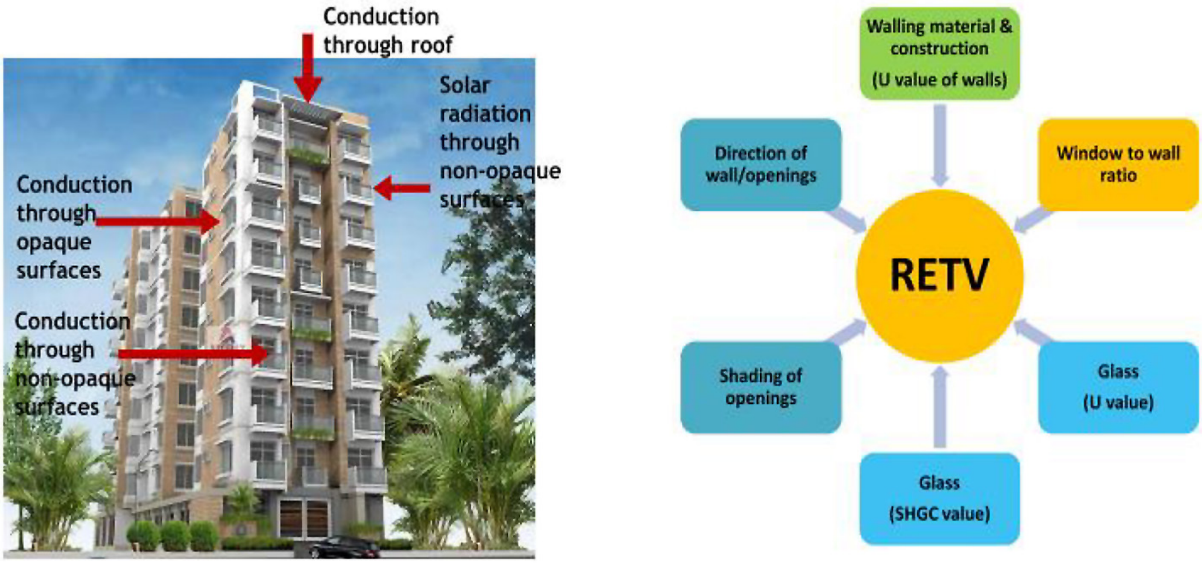

Figure 4. Building RETV in coordination with BE factors (Congress, 2019)

climate zones and then compared with over 20 BE retrofitting scenarios, including wall insulation, window upgrades, and passive strategies. Petidis et al. (2018), reported that a comprehensive retrofit strategy, starting with a calibrated base case model, can greatly enhance the energy efficiency of outdated social buildings. He concluded that the simulation of retrofits resulted in 10%, 1.7%, 14.6%, and 17.4% savings in energy. Bataineh & Al Rabee (2021) investigated a base-case simulation model of the existing building. It was calibrated and verified using real-time experimental data and so on.

The guidelines from urban planning, sustainable and Government bodies

Data from many urban planning bodies, the Sustainable Building Council, and the partnership of Government and Semi-Government policymakers. The Delhi Development Authority (DDA) and the Ministry of Housing and Urban Affairs (MoHUA) emphasise the role of housing scenarios for low-rise apartment buildings through bylaws and sustainable practices. The National Sample Survey Organisation (NSSO) reviews the old building structures along with the number of their inhabitants. The National Institute of Urban Affairs (NIUA) report, "Rental Housing in a Metropolitan City: A Case Study of Delhi", highlights the diversity of rental housing options in the city, including low-rise apartments. The Bureau of Energy Efficiency (BEE), a statutory body under India's Ministry of Power, helps develop policies to lower the country's energy consumption intensity. The Ministry of Power has introduced the Eco-Niwas Samhita 2018, part of the Energy Conservation Building Code (ECBC) for residential structures. This section outlines guidelines for creating energy-efficient building envelopes. The Indo-Swiss Building Energy Efficiency Project (BEEP) is an international collaboration between India's Ministry of Power and the Swiss Confederation's Federal Department of Foreign Affairs. The project's ultimate purpose is to use energy-efficient and thermally comfortable design to save energy.

The review of the above literature highlighted several important variables that can be presented for a clearer understanding of the relationships between the variables involved in this study. Table 4 presents a structured synthesis of the variables and factors discussed in the reviewed literature, aligning them with the corresponding studies. It demonstrates how various elements, including climate parameters, RETV, thermal comfort, and building envelope strategies (such as insulation, glazing, shading, airtightness, and material choices), have been examined in relation to energy efficiency outcomes. Table 4 also highlights the contribution of simulation tools, energy codes, and compliance frameworks in assessing retrofitting measures and energy savings.

Table 4. Variables/factors relation with citations of past studies by Authors

Factors/variables	Citation
Climate parameters, RETV, thermal comfort, building envelope design & modification strategies (walls, insulation, windows, WWR, shading, air tightness, finishes, materials, envelope retrofits), building characteristics (location, orientation, age, size, types)	Ghazwani et al., 2025; Monné-Bailo et al., 2024; Lozoya-Peral et al., 2023; Nutakki et al., 2023; Xu et al., 2021; Ge et al., 2021; Mushtaha et al., 2021; Tewari et al., 2019; Naveen Kishore & Rekha, 2018; Arab et al., 2017; Khambadkone & Jain, 2017; S, 2022; Mathur & Damle, 2021; Shandilya et al., 2020; Nasir et al., 2023; Felimban et al., 2019; Sachar Sneha et al., 2018; Almasri & Alshitawi, 2022; He et al., 2021; Saikia et al., 2020; Apeksha Shandilya & Streicher, 2017; Kumar et al., 2017; Petidis et al., 2018; Kamel & Memar, 2016; Alaidroos & Krarti, 2016; Bataineh & Al Rabee, 2021; Biju & Ayyathurai, 2019; Jeong et al., 2017; Farjami & Mohamedali, 2017
Building energy efficiency, energy codes, energy consumption & energy savings, Air-conditioning usage / ac's energy, simulation tools & techniques / building energy modelling, potential retrofitting analysis (envelope modifications, passive strategies, code compliance, energy savings potential, cost–benefit)	Berwal & Yadav, 2021; He et al., 2021; Shandilya et al., 2020; Naveen Kishore & Rekha, 2018; Petidis et al., 2018; Kamel & Memar, 2016; Monné-Bailo et al., 2024; Lozoya-Peral et al., 2023; Nutakki et al., 2023; Almasri & Alshitawi, 2022; S, 2022; Ge et al., 2021; Homod et al., 2021; Mushtaha et al., 2021; Ciardiello et al., 2020; Saikia et al., 2020; Ijasahmed et al., 2019; Fan & Xia, 2017; Farjami & Mohamedali, 2017; Felimban et al., 2019; Sachar Sneha et al., 2018; Nasir et al., 2023; Biju & Ayyathurai, 2019; Apeksha Shandilya & Streicher, 2017; Kumar et al., 2017; Ghazwani et al., 2025; Xu et al., 2021; Jha & Bhattacharjee, 2018

IDENTIFYING RESEARCH GAPS

Numerous studies have explored building envelope retrofitting strategies aimed at enhancing energy efficiency and improving indoor thermal comfort across various climatic regions. These studies cover a range of building types, climatic conditions, and retrofitting strategies, including both simulation tools and fieldwork experiment methods. Still, despite all the progress in research, some critical areas have not been thoroughly examined and remain underexplored, especially in a composite climate like New Delhi. The following justification highlights the key research gap identified through the competitive analysis:

1. There is a lack of region-specific retrofit models and comparative studies for composite climates like Delhi, as well as the absence of climate-responsive guidelines that integrate sustainability metrics such as life-cycle carbon footprint.
2. There has been limited attention to high-rise buildings, which are common in urban India, as most of the retrofitting studies focus on separate homes and public buildings. Simulation and field validation for high-rise retrofits remain scarce.
3. RETV analysis is underutilised, as few studies employ it comprehensively, mainly in field-based retrofitting tasks. However, RETV is very rarely used in design validation for existing residential apartment buildings. It could be integrated into simulation and benchmarking across retrofit scenarios.
4. Passive measures such as vertical greenery, shading vegetation, and green walls are rarely tested, and there is little research combining passive retrofitting with active cooling technologies to move towards net-zero residential energy use.
5. Limited consideration of occupant behaviour and feedback. Few papers, Felimban et al. (2019), and Xu et al. (2021) discuss the user behaviour. However, most simulations lack real-time validation with occupant surveys or adopted comfort models.
6. Neglect of cost-effectiveness and payback in the Indian context. Only some international studies assess cost-benefit analysis and payback periods. However, Indian retrofitting studies seldom do this for existing residential apartments or buildings.
7. Limited material innovation in Indian studies, although some innovative materials (EPS, XPS, rockwool, foam, and reflective glass) are examined, sustainable local materials (composites, lime plaster, and human hair-based insulation) are overlooked, mainly in composite climate studies.
8. There is no standardised framework for retrofitting strategies, such as comparative benchmarking across different climatic zones. Furthermore, a consistent matrix, like RETV, EPI, and payback, is lacking to assess the uniform impact of retrofitting.

CONCLUSIONS

The review examines sustainable retrofitting strategies for residential building envelopes in the composite climate of New Delhi, with a focus on reducing energy consumption, particularly from air conditioning. These reductions also contribute to environmental benefits by decreasing peak electricity demand, reducing greenhouse gas emissions, and enhancing resilience against climate-induced impacts stresses.

Several simulation tools, such as Design Builder, Energy-Plus, and TAS, are introduced to evaluate energy performance after retrofitting. Findings from prior studies indicate that retrofitting strategies, including wall insulation, efficient glazing, shading, and airtightness, can reduce energy consumption by 20–60%. Guidelines from BEE, TERI, and the Eco-Niwas Samhita (ENS) emphasise envelope-focused solutions, including RETV analysis, a key metric for evaluating thermal performance. Also, very few studies were seen through the low-rise apartment energy study, and the proposed composite climate was not considered in most of studies.

This reviews also indicate that wall insulation was installed to reduce energy consumption in residences. However, this was mainly relevant to hot, dry climates and other regions, but not to the Indian composite climate context. Predominantly, retrofitting methods were adopted in many Western countries. Due to the significant issues of electrical crises and high greenhouse gas emissions in India today, more time is required to develop effective strategies for the Indian context. Inhabitants' reliance on air conditioning is increasing because of the extreme weather conditions associated with the composite climate during summer and the air pollution situation in Delhi.

Overall, this study confirms the achievement of goals as it clearly states that the review successfully identified and synthesised retrofitting strategies specific to the composite climate of New Delhi.

It highlights new insights by emphasising that the paper consolidates dispersed findings into a structured framework, identifies gaps as RETV remains underutilised in composite climates, and cost-effectiveness frameworks are rarely applied. By consolidating simulation and field-based evidence, this paper fills a critical gap in identifying retrofit models tailored for New Delhi's composite climate.

Additionally, it contributes to knowledge by presenting a comprehensive framework that combines climate-specific retrofit measures with RETV evaluation and cost-effectiveness, a consideration that previous studies have neglected. These insights open prospects for developing region-specific guidelines, integrating occupant behaviour, and validating hybrid passive-active retrofits and innovative materials, ultimately supporting India's pathway toward sustainable and low-energy housing.

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