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Original Article

Optimal Window-to-Wall Ratio (WWR) for Perceived Satisfaction with Natural Ventilation: A Post-Occupancy Evaluation in Affordable Housing of Kolkata, India

Sujoy Biswas[1*], Arjun Mukerji[1]

[1]*Department of Architecture and Regional Planning, Indian Institute of Technology (IIT) Kharagpur, India.*

[*]*Corresponding Author : sujoy6@iitkgp.ac.in*

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Abstract - *This study's purpose was to identify the optimal Window-to-Wall Ratio (WWR) that maximises homebuyers' perceived satisfaction with natural ventilation in affordable housing in the hot and humid climate of Kolkata, India. The methodology employed a rigorous, user-centric, quantitative approach. Data was gathered through a large-scale post-occupancy survey, collecting 383 valid responses from residents across 32 affordable housing complexes. Perceived satisfaction with natural ventilation was quantified using the Percentage of Scale Maximum (%SM) method from five-point Likert-type scale responses. Residents' perceived satisfaction was correlated with the measured WWR of each complex. Using polynomial regression, a predictive mathematical model was derived to assess the non-linear relationship. The findings identified an optimal WWR range of 24–33%, with the mathematical peak satisfaction (at 97.5%) occurring at a WWR of 33.31%. Beyond this range (either below or above), the predictive mean satisfaction falls. The originality of this research is its innovative integration of perceived satisfaction with a quantifiable design parameter (WWR) in the affordable housing sector, shifting the research paradigm from a traditional, energy-based assessment to a human-centric adaptive comfort model, and using a predictive mathematical model to calculate optimal WWR based on post-occupancy residents' perceived satisfaction in a hot and humid climate*.

Keywords - *Affordable Housing, Perceived Residents' Satisfaction, Post Occupancy Evaluation, Window Wall Ratio (WWR), Percentage Scale Maximum (%SM), Polynomial Regression, Mathematical Optimisation.*

1. Introduction

Rapid urbanisation has transformed the landscape of affordable housing in many Indian metropolitan regions [1]. Even as the demand for affordable housing continues to rise, a large number of completed units remain unsold [2]. This situation points to more than a market imbalance; it reflects a deeper issue in how these dwellings respond to buyers' needs and lived expectations [3]. Affordable housing projects often prioritise cost efficiency and regulatory compliance over user comfort or adaptability, leading to a mismatch between what is built and what residents actually value in their living environments [4]. Due to rising property prices, higher population density, and to provide 'Housing for All', the developers try to deliver compact, densely packed housing units at an affordable price [5].

In such housing markets, the quality of the living environment depends not only on the size of the dwelling but also on how effectively design features support comfort and functionality. Among these features, natural ventilation plays a central role in hot–humid climates, offering a low-cost means of thermal relief and shaping residents' perception of livability [6]. The configuration of window openings, and specifically the Window-To-Wall Ratio (WWR), thus becomes a critical design parameter, linking economic constraints with climatic realities and directly influencing how homebuyers experience their homes [7].

Kolkata city, India's one of the Tier-1 cities, experiences a hot and humid tropical climate, characterised by extended summers, high relative humidity, and minimal diurnal temperature variation [8]. Under such conditions, natural ventilation becomes one of the most crucial factors in determining indoor comfort and perceived livability. At the same time, Kolkata's dense urban morphology, characterised by compact plots, minimal setbacks, and high site coverage, restricts the scope for cross-ventilation [9].

Most apartments are built in tightly packed clusters where facade openings serve as the primary means for air movement. Nevertheless, design decisions about window proportions are often driven by cost or appearance rather than climatic performance. Studying this context enables an assessment of how architectural configuration, specifically WWR, affects

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residents' satisfaction within the real-world constraints of density, economy, and climate [10].

Previous research studies by the authors have examined the relationship between residents' perceived utility with various housing attributes and the percentage sales and found that the buyers' preferences directly impact affordable housing market performance in the Kolkata Metropolitan Area (KMA). Further, the authors found several aspects of homebuyers' satisfaction. They identified eight significant indicators of residents' satisfaction under two latent constructs: building-level satisfaction and neighbourhood-level satisfaction, and only two indicators were recognised where the developers can intervene and improve, namely 'Natural Ventilation' and 'Carpet Area'.

Natural ventilation, however, is not an abstract concept; it is strongly governed by measurable design parameters such as WWR [11]. Existing research literature overwhelmingly usually treats WWR as an engineering variable, often optimised through simulation for energy efficiency, daylighting, overheating mitigation, and users' thermal and visual comfort. However, few studies have examined the impact of WWR on building energy performance, daylighting, and thermal comfort. It is worthwhile to note that there is limited research linking evaluating residents' perceived satisfaction with natural ventilation in terms of measurable design parameters such as WWR, particularly in the hot and humid climate the climatic context of Kolkata.

1.1. Research Gap

A research gap exists in understanding how facade design variables translate into subjective comfort, or say 'perceived satisfaction', under a hot and humid climate. This study shifts the research focus from a *Physics-Centric* model to a *Human-Centric* adaptive comfort evaluation for households that have already bought the properties.

Mostly, the research studies (systematically presented in Section 2.1) on WWR are simulation-based research in India, which have examined WWR in relation to daylight performance, cooling loads, energy efficiency, and code compliance across diverse climatic zones. However, very few studies connected the technical findings to actual user experience or, say, users 'perceived' satisfaction (further discussed in Section 2.2). The natural ventilation aspect remains remarkably underexplored in the 'affordable housing' sector, even though households belonging to this segment mainly depend upon passive ventilation with limited access to mechanical cooling.

1.2. Research Question

The current study focuses specifically on natural ventilation as a measurable dimension of residential satisfaction. It examines the relationship between the Window-to-Wall Ratio (Which Represents The Proportion Of Window Area To Total Wall Area On A Building Facade) and Residents' *perceived satisfaction with* natural ventilation. Understanding this relationship can help developers with practical and evidence-based guidance for improving housing design quality without incurring significant cost escalation. This leads to the formulation of the following research question;

Research Question: What is the optimal Window-To-Wall Ratio (WWR) that maximises homebuyers' satisfaction with natural ventilation in the affordable housing for a hot and humid climate city like Kolkata?

To answer this, the study establishes a quantitative relationship between residents' satisfaction levels and corresponding WWR values. Further, a predictive model is developed to identify the minimum WWR required to achieve satisfaction potential and the optimal WWR that yields the highest overall residents' satisfaction in hot and humid regions such as Kolkata.

This research paper consists of five sections. Following the introduction, Section 2 presents the literature review, while Section 3 outlines the research methodology, Section 4 highlights the results and presents discussion, and finally, Section 5 concludes the study with key findings, contributions, limitations, and future scope of the study.

2. Literature Review

The Window-To-Wall Ratio (WWR) has usually been recognised as a crucial parameter in building design, and its influence on thermal loads, daylighting, and energy efficiency. Over the past decade, research has largely approached WWR as an engineering variable, optimised through simulation models to achieve thermal comfort. While this body of work has advanced our understanding of envelope behaviour, it has paid little attention to how residents themselves perceive ventilation, openness, or comfort-factors that are especially important in compact, affordable housing units in hot–humid climates such as the Kolkata Metropolitan Area (KMA). This review synthesises the existing literature to highlight dominant research trajectories, identify gaps, and establish the rationale for a user-centred study of WWR.

2.1. Systematic Literature Review

The search for previous studies was conducted across various research portals like Web of Science, Scopus, DOAJ, and Google Scholar for the last decade. Nearly 1,034 articles were identified as potentially relevant to the current study of the Window-To-Wall Ratio (WWR). After the initial filtering, 437 abstracts were read thoroughly, covering journal articles, conference papers, theses, and review studies. Following this, approximately 150 studies were shortlisted as relevant to the window-to-wall ratio in relation to both users' comfort and energy efficiency. Of these, a final set of 70 studies that directly examined WWR, which were fully accessible, was considered in this study. The studies are discussed in the following sub-sections, divided into two major groups: Indian and international cases.

2.1.1. Indian Cases

In 2014, Samanta et al. [12] studied external shading effects on the cooling demand using TRNSYS 17 simulations for a residential guest house (in a tropical climate) in Asansol, India. They found that movable shading on east–west side facades and WWRs of 10–18% reduced cooling loads by 8%. Meanwhile, Bose and Sarkar [13] compared the thermal comfort in low-rise housing (7°C higher than lower floors) and traditional buildings. They found that WWR around 10–15% resulted in inadequate ventilation and thermal discomfort.

In 2016, Debnath and Bardhan [14] studied the WWR's effect on daylight performance using DAYSIM/Radiance simulations for high-rise residential buildings of Mumbai, India. They found that a South-East orientation with a WWR of 50% had delivered 63% more useful daylight, effectively reducing the energy demand from artificial lighting. Gokarakonda and Kumar [15] had compared passive cooling loads and energy efficiency codes for buildings in India. They found optimal daylighting (with a WWR between 10 to 30%). They also mentioned that the Indian energy conservation building code has allowed much higher WWR, which might result in detrimental cooling loads.

In 2018, Krishnan [16] had compared the WWR requirements for buildings in various Tier-1 cities of India (using EnergyPlus simulation), and found optimal WWR of 20–30% for the hot-dry climate of Ahmedabad, 30–35% for the warm-humid climate of Mumbai, and 30–40% in the composite climate of Delhi. Whereas, Sharma et al. [17] assessed the passive cooling loads and visual comfort in buildings across seven Indian cities (using TRNSYS and DIVA simulations). They found that both cooling and heating loads had increased with the rise of WWR from 15 to 60%.

Meanwhile, in 2019, Bhanware et al. [18] found a reduced cooling load (using a correlation test) for the housing units (from seven Indian cities) when the WWR was 15%.

In 2020, Barman et al. [19] realised that openable WFR in housing complexes of Guwahati, India, was only 13.47% (which was below the NBC minimum of 16.66%). Using the WFR, RETV, U-values, and WWR calculations, they further concluded that a higher WWR was required with stricter VLT glazing limits to control the heat gain of the building.

Further, Dubey and Ahmad [20] mentioned that the electricity usage had increased (~60.8 MWh to ~67.7 MWh and EUI from 1606 to 1722) when WWR was converted from 30 to 90% for the institutional buildings in Aligarh, India, using a Revit-based simulation.

In 2021, Agarwal and Samuelson [21] used EnergyPlus simulations to find that overall envelope transmittance was a significant factor of severe overheating (while having a WWR of 30%) in affordable housing of Ahmedabad and Kolkata, India.

Sahu et al. [22] had used 'EnergyPlus' and 'COMFEN' simulation software to find optimum WWRs of 20% for the north facade, 18% for the south facade, and 10–15% for the east and west facade. It had reduced the baseline Energy Performance Index while meeting the minimum daylight requirements in office buildings in Bangalore, India.

Kumar et al. [23] used eQUEST software. They found that optimised glazing in high-rise residential apartments of Kolkata, India (with a WWR of 17 to 37%) had resulted in an improved energy savings of 7.9–25.6%.

Mohanta et al. [24] found that an optimal WWR below 40% with passive shading and double-glazing for commercial buildings in Kolkata, India. Raihan et al. [25] used EnergyPlus software and found that semi-transparent photovoltaic and electrochromic glazing performed best at 30–40% WWR for residential and commercial buildings in Hyderabad, India. These glazing types helped in reducing the annual energy usage by 5–15%.

Vishnubhotla et al. [26] used IES-VE simulations and found an optimal climate-specific WWR of 20% (reduced indoor temperatures by up to 2.6 °C) for the residential buildings in Tiruchirappalli and Coimbatore, India.

In 2023, Keshri and Dey [27] used the OpenStudio simulations to find the appropriate WWR in social housing projects of five Indian cities. They found that out of five case studies, only two had a suitable WWR (optimal at ≤38%). They further found that after optimising WWR and orientation, the energy usage had reduced, ranging from 0.5 to 7.2%.

Nihar et al. [28] used EnergyPlus simulations (with an airflow–pollution model) to assess natural ventilation in informal housing (with a WWR of 15%) of Delhi and Bangalore, India. They found that, after adding low-cost MERV-14 filters, the natural ventilation hours had increased by 25%.

Venkatesh et al. [29] used building information modelling-based simulations (such as Revit, Navisworks) to study WWR and orientation effects on energy consumption in multi-storey residential buildings in Kakinada, India. They found that a WWR of 20% (with a 90° orientation) had minimized the electricity demand, whereas increasing the WWR to 100% resulted in an increased annual consumption by 43%.

In 2025, Chaturvedi et al. [30] reviewed 44 NZEB case studies from the USA, China, and India. They mentioned that the Indian NZEBs usually underperformed compared to the global benchmarks, which typically featured the Window-To-Wall Ratios (WWR), ranging between 30% and 45%.

Chaturvedi et al. [31] had used the EnergyPlus simulations to improve the residential envelope design in Jaipur, India. They found that optimised south and west-facing WWR (with shading) had improved the daylighting six times, and cut cooling energy load by 72% in India's composite semi-arid climate.

In 2025, Ahmad et al. [32] used EnergyPlus and eQuest software and found that for north-facing fenestrations, a WWR of 10% had reduced the energy loads by 28.6%, while for the west-facing fenestrations, a WWR of 40% had increased the energy demands substantially for the residential buildings in Ranchi, Jharkhand.

Chanda and Biswas [33] had used the fuzzy TOPSIS and EnergyPlus simulation methods. They found the optimal WWR ranging between 30 to 36% across various vernacular climates of India.

Although extensive simulation-based research in India has examined the WWR in relation to daylight, cooling loads, energy performance, and code compliance across diverse climatic zones, a significant gap persists in linking these technical findings to actual user experience. Moreover, the ventilation aspect for the affordable housing markets was largely unaddressed, even though these housing typologies largely depend on natural ventilation-driven design due to limited mechanical cooling facilities to afford.

2.1.2. International Cases

In 2016, Alibaba [34] used the dynamic thermal simulations (EDSL Tas) method to optimise WWR and thermal comfort in office buildings of Famagusta, Cyprus. They found that an optimal WWR of 10%, based on Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indices. Rashid et al. [35] found an optimal WWR ranging between 20% and 30% for commercial buildings in Lahore, Pakistan.

In 2017, Yassin et al. [36] employed the Rhino with Diva plug-in simulations to optimise the WWR for daylighting. They found that WWRs ranging between 30 to 55%, substantially improved the daylighting requirement of 300 lux for the residential buildings in Mansoura City, Egypt. Feng et al. [37] used the EnergyPlus simulation method to find the optimal WWR for the residential buildings of Shenyang, China. They found the optimum WWR ranging between 10 to 15% for the east-west facade, and 10 to 22.5% for the south facade.

Wen et al. [38] used the EnergyPlus simulation tools to determine the optimal WWR for commercial buildings in Japan, and found the optimum WWR ranged between 30% to 50% for warm regions, and 60% to 70% in cold regions.

In 2018, Azmy and Ashmawy [39] used the EnergyPlus simulations to analyse WWR effects on energy and daylighting in the administrative buildings of Cairo, Egypt. They found optimal WWR ranging between 20% to 30% when coupled with strategically placed upper openings, which resulted in 29% lower annual energy usage.

In 2019, Troup et al. [40] used the parametric analysis method to analyse the energy usage in the commercial buildings of the US. They found that the optimal WWR was ≤ 40%, while beyond this, the energy usage had increased substantially.

Pathirana et al. [41] used the DesignBuilder and EnergyPlus simulation software on the residential buildings of Sri Lanka to measure the WWR's impact on houses in a tropical climate. The optimal WWRs range from 20% to 30%. At this WWR the thermal comfort had increased from 20% to 55%.

Ziabari et al. [42] used the DesignBuilder/EnergyPlus simulations in office buildings of Rasht, Iran, to evaluate energy loads. They found the best WWR of 30% for the south facade, while ≤ 20% for the west facade, for sustainable energy usage.

Shaeri et al. [43] conducted 'DesignBuilder' and 'EnergyPlus' simulations to evaluate the energy loads for office buildings situated in the hot-humid climate of Bushehr, the hot-dry climate of Shiraz, and cold climates in Tabriz, Iran. They found that the optimal WWR ranged from 20 to 30%.

In 2020, Alsehail and Almhafdy [7] measured building thermal performance in Saudi Arabia. They found optimal WWR ranging between 10 to 20% for the hot and dry climates, whereas 38% to 42% for the temperate climate regions.

Chi et al. [44] had used the Ecotect and the PHOENICS simulation (Parabolic, Hyperbolic or Elliptic Numerical Integration Code Series) software to determine the optimal WWR for traditional (Sizhai style) dwellings in Zhejiang Province, China. They found the ideal WWR between 30 to 40%.

Li et al. [45] employed the 'ENVI-met' simulations on residential buildings in Chenzhou, China, to study thermal environment regulation by WWR. They found an optimal WWR < 40% for thermal comfort and sustainable energy usage.

Bulus [46] had used the 'IES-VE' (Integrated Environmental Solutions – Virtual Environment) on courtyard houses of Nigeria to evaluate the indoor thermal comfort. He found that indoor thermal performance had improved significantly with a WWR of 16%.

In 2021, Liu et al. [47] conducted energy and load evaluations on residential buildings in Shanghai, Zhejiang, and Jiangsu, China. They found an optimal WWR ranged between 30% to 40%.

Veillette et al. [48] had used the 'TRNSYS' (Transient System Simulation Tool) simulations on a social housing residential building in Quebec City, Canada, to evaluate the energy loads. They mentioned that increasing WWR from 13% to 20-40% had raised the heating demand.

Sayadi et al. [49] employed the 'IDA-ICE' simulations on residential and commercial buildings of Iran and Sweden to evaluate the thermal comfort. They found minimal annual energy consumption with WWR between 30 to 45%, improving thermal comfort with appropriate shading and low-U glazing fenestration solutions.

Koohsari and Heidari [50] used the EnergyPlus, Radiance, and Daysim simulations on office buildings in Rasht, Iran, to evaluate the energy loads. They highlighted the optimal WWR ranging between 15–25% (best at 19.8%), reducing annual primary energy and electric lighting demand by 40% while maintaining occupants' visual comfort.

Saber [51] had conducted the DesignBuilder simulations for residential buildings in Tabriz (semi-arid climate), Iran, to evaluate the overall heat gain. She found that minimum energy use was at WWR 5%, while the optimal balance for lighting and comfort was found to be 45–55%. She further added that recycled ash concrete panels provided better energy reduction compared to porous concrete.

Albatayneh et al. [52] had used the DesignBuilder simulations for a residential building in Amman, Jordan. They had examined how efficient modern LED lighting affects WWR optimisation. They found an optimal WWR range of 25% to 30%.

In 2022, Rana et al. [53] used the 'eQUEST' (Quick Energy Simulation Tool) simulation software to find optimal WWR. They found an optimal WWR ranging between 30% to 40%.

Shrestha and Shakya [54] used the Ecotect modelling to examine WWR and natural ventilation in residential buildings of Janakpur, Nepal. They found that a WWR of 20% had minimised the heating and cooling demands. In 2023, Al-Yasiri et al. [55] used the EnergyPlus model to examine the PCM envelopes with night ventilation in a residential real estate of Al Amarah, Iraq. They found nighttime comfort increased when WWR was increased from 8.75% to 20% in northeast-facing windows, and reduced the temperatures by 31%. Rangel et al. [56] had used the DesignBuilder simulation tools on residential and office buildings of Bucaramanga (having a tropical climate), in Colombia, to calculate the overall heat gain. They found an optimal WWR of 16–25% for residential and < 50% for commercial buildings, respectively.

In 2024, Kitsopoulou et al. [57] mentioned that a WWR below 40% was ideal for buildings in warm climates and a WWR of 20% to 30% for colder regions, across Europe and Asia.

Pourtangestani et al. [10] suggested a WWR between 30% and 40% for optimal Indoor Air Quality (IAQ), thermal comfort, and energy efficiency.

Onochie et al. [58] used the statistical correlation tests to investigate the relationship between WWR and ventilation in residential buildings of Enugu State, Nigeria. They are finding an optimal WWR ranging from 30% to 50%.

Yi et al. [59] used the EnergyPlus software with jEPlus parametric simulation and 'Monte Carlo' analysis to assess the energy loads in various buildings of Shanghai, China. They found WWR between 30% to 40%, strongly shaped solar gains and ventilation, while shading devices reduced cooling loads by up to 3%.

Wei et al. [11] found that an optimal WWR of 30% was observed in a workshop in Penang, Malaysia. Yin et al. [60] conducted a global literature review using Artificial Neural Networks (ANN). They identified WWR as a dominant predictive variable for thermal heat comfort. They found that the optimal WWR ranged between 30% to 50% for mixed and hot-humid climates, while 10% to 30% for the cold regions.

Hassieb et al. [61] used the 'Design Builder' simulation software to evaluate thermal comfort in a school building in Aswan, Egypt. They found an optimal WWR of 20%.

Koyun et al. [62] used the Simplex optimisation method to calculate the optimum heat transfer and minimum cost analysis for a residential building in Antalya, Turkey. They found the optimal WWR of 30% with suitable glazing and walls.

Tawfeeq and Qaradaghi [63] used the Revit simulations to optimise the WWR for low-rise apartments in Sulaimaniyah, Iran. They found facade-specific optima with WWR of 65% for south and east, 95% for north, and 30% for west-facing fenestration.

In 2025, Kalathoki [64] used simulation tools to evaluate optimal WWR for residential buildings across multiple climatic zones in Nepal. He found that WWR ranging from 15 to 25% minimised the cooling loads in hot regions, while WWR ranging from 30% to 40% balanced the daylight and heating in temperate and cold regions.

Wu et al. [65] used the Rhino software with Grasshopper, Ladybug Honeybee, and NSGA-II optimisation plug-ins to evaluate fenestration and shading efficiency for the office buildings in Sanya (having a hot-humid climate) of China. They found that a WWR of 60% provided the best trade-off between energy, comfort, daylight, and view quality simultaneously.

Xia et al. [66] used the Rhino software with Grasshopper, EnergyPlus, NSGA-II, and GPR tools to optimise window design in school buildings of Guangzhou, China. They found optimal WWR at 40%, with a reduction in energy loads by 6.7%, and improvement in thermal comfort by 14.3% in a hot and humid climate.

Yang et al. [67] used the EnergyPlus and the OpenFOAM-CFD simulation tools to assess WWR in traditional houses in Kunming (having a subtropical highland climate), in China. They found an optimal WWR ranging between 10 to 15%, balancing the thermal comfort and limiting the winter heat loss.

Cheng et al. [68] used the TRNSYS simulations to analyse thermal mass, glazing, and WWR interactions in public buildings of Qingdao, China. They found that WWR < 50% (with double glazing) was ideal for reducing the overheating issues.

Gigasari et al. [69] used the TRNSYS18 to study WWR in apartment buildings across five global climates. They found that the optimal WWRs were 10% for south facades and 60% for north facades, resulting in a 56% reduction in energy loads.

Alwetaishi [70] utilised the EDSL-TAS simulations to assess the ideal WWR in residential buildings in Taif, Saudi Arabia. He recommended an optimal WWR of <20% as the indoor temperature rises by ~1 °C per 10%.

Abdullah et al. [71] used Autodesk Revit software to assess required daylighting in classrooms at Universiti Teknologi Malaysia, Skudai. They found an optimal WWR of 30% or higher.

Liu et al. [72] utilised the 'TRNSYS18' simulation software to evaluate thermal comfort in office buildings in Qingdao, China. They found that a 30% WWR with double glazing achieved optimal performance and reduced energy loads by up to 500 kWh.

Alramthan et al. [73] used the MATLAB-RTS software to calculate the cooling loads in office buildings in Kuwait. They found an optimal WWR ≤50%

Bera and Nag [74] conducted a global literature review of building energy strategies. They found an optimal WWR ranging between 20 to 40% for reducing heating and cooling demand.

Ma'bdeh et al. [75] used the Revit and ANSYS CFD simulation tools on the commercial buildings of Irbid, Jordan, to evaluate WWR efficiency. They found an optimum WWR of 30% for ideal ventilation.

Oliveira [76] used the EnergyPlus simulations to measure the thermal comfort for the office buildings in Fortaleza (having a warm-humid climate), in Brazil. He found that WWR ≤ 62% substantially improved the thermal comfort and energy efficiency.

A review of the literature shows that approximately 75 to 80% of all studies originate from Asia (mainly India, China, and Iran). In comparison, Europe contributes 8% to 10%, North America 5% to 6%, Africa 4% to 5%, South America 3% to 4%, and Oceania 1% to 2%. This indicates a strong need to study the vivid climatic conditions of the Asia continent. Furthermore, studies on natural ventilation in the affordable housing segment globally have remained underexplored, where reliance on passive ventilation is at its highest possible due to limited mechanical cooling facilities.

2.1.3. Inference from the Literature Review

At the global level, the literature shows that nearly 75% to 80% of studies are concentrated in Asia, primarily from India, China, and Iran, and minimal contributions from other continents, indicating the need for broader climatic representation. Even in Asia, the studies rarely addressed natural ventilation performance in the 'affordable housing' segment. Importantly, no existing research has focused on the Kolkata housing market, nor has any study examined residents' perceived satisfaction with WWR and natural ventilation in the affordable housing segment, leaving a significant contextual and experiential gap in current knowledge.

3. Methodology

3.1. Sample

The survey was conducted across thirty-two private affordable housing complexes in Kolkata, selected from 259 projects identified via magicbricks.com and 99acres.com. As per the definition given by the Government of India, houses priced up to ₹50 lakh and with a carpet area of < 60 m² are considered affordable housing units. Access to the housing complexes and the conduct of social surveys required the consent of developers or housing associations. The sample was shaped by the permissions granted (purposive sampling).

These complexes comprised a total of 4,549 affordable units (41.13% of all units), of which 4,152 were sold. For small populations using Cochran's formula with 95%

confidence and a 5% error margin, the minimum sample size required was 352. An additional 10% responses were added to account for possible incomplete data, resulting in interviewing around 390 respondents. Finally, 383 valid responses were considered for the study.

To capture residents' subjective evaluation of their ventilation quality, a five-point Likert-type scale survey instrument was employed. Respondents rated their satisfaction as: 1 for 'Disliked', 2 for 'Tolerated', 3 for 'Neutral', 4 for 'Expected', or 5 for 'Liked'. For analytical consistency, the scores were converted into a proportional scale ranging from 0 to 1. Finally, the mean satisfaction values were computed for each housing complex, enabling a comparative dataset with 'Natural Ventilation' performance.

3.2. Calculation

To calculate percentage satisfaction, this research used the empirical method introduced by Cummins [77]. This technique transforms the Likert-scale responses into a standardised metric also known as the Percentage of Scale Maximum (%SM). It has key assumptions: first, that the scale accurately reflects 'Perceived Satisfaction', and second, that the data originate from 'comparable' samples. This study met these conditions since the samples were drawn from similar groups across 32 housing complexes in Kolkata. Furthermore, the method requires a balanced scale with a minimum of four response options and a sample size of at least 200 participants, both of which were met, given that more than 380 respondents participated. The %SM approach converts Likert scores into a uniform range from 0 to 100, assigning 0 to the lowest anchor (e.g., 'Dislike') and 100 to the highest (e.g., 'Liked')—allowing the mean score to be expressed in %SM units as follows:

$$\%\mathrm{SM}_i = \frac{s_i - 1}{s_{max} - 1} \times 100 \quad (1)$$

$\%SM_i$: Percentage of user satisfaction for the i^{th} variable
s_i: Mean user satisfaction for the i^{th} variable
s_{max}: Maximum possible user satisfaction

The study operationalised natural ventilation performance using the Window-to-Wall Ratio (WWR) as a quantifiable architectural indicator. WWR values for each project were obtained through the floor plans and unit layout dimensions, provided by the developers. By correlating the WWR of each housing complex with the corresponding mean satisfaction levels of residents, the study established a relationship between WWR and perceived satisfaction with natural airflow.

Table 1. Comparison of actual and predicted satisfaction based on WWR for the selected housing complexes

S.No.	Project Name	WWR (Decimal)	Satisfaction (%SM)	Predicted Satisfaction	Sq. Residual (e^2)
1	Anjali Greens	0.2243	0.9583	0.565	0.155
2	Arjavv Sonarkella	0.2934	0.7708	0.920	0.022
3	Bhawani Courtyard	0.1913	0.3100	0.279	0.001
4	Debomita Apartment	0.2490	0.9091	0.730	0.032
5	Eden City	0.2498	0.9583	0.735	0.050
6	Freshia	0.3598	1.0000	0.950	0.003
7	Gitanjali	0.1841	0.1042	0.207	0.010
8	Godrej Prakriti	0.3260	0.9583	0.973	0.000
9	Grande One	0.2288	0.8542	0.598	0.066
10	Hiland Green	0.2591	0.5833	0.785	0.041
11	Khushi Residency	0.2197	0.2167	0.530	0.098
12	Mayfair Platinum	0.2276	0.4583	0.589	0.017
13	Meena Graciya	0.2676	0.7708	0.826	0.003
14	Meena Orchid	0.3339	0.9583	0.975	0.000
15	Metro Height	0.3223	1.0000	0.971	0.001
16	Mira Garden	0.2774	0.8542	0.867	0.000
17	Oxford Square	0.2642	1.0000	0.810	0.036
18	Porospathar	0.2769	0.9583	0.865	0.009
19	Radha Kunja	0.2091	0.4375	0.442	0.000
20	Rajashi Enclave	0.2176	0.7292	0.513	0.047
21	Rajwada Emerald	0.2011	0.4125	0.371	0.002
22	Sapnil Residency	0.2292	0.2167	0.601	0.147
23	Siddha Suburbia	0.2676	0.7708	0.826	0.003
24	Siddha Waterfront	0.2638	0.7292	0.808	0.006
25	Sonar	0.2778	0.9583	0.869	0.008
26	Spotlight	0.2551	0.8542	0.764	0.008

27	Sunland	0.2647	0.9167	0.813	0.011
28	Swagat Skyline	0.2144	0.2500	0.487	0.056
29	Tirath	0.2911	0.8542	0.914	0.004
30	Tirupati	0.2542	0.5375	0.759	0.049
31	Ujjivan	0.1808	0.2500	0.172	0.006
32	Xanadu	0.3201	0.9167	0.969	0.003
Source: Primary Data and authors' calculations (done in MS-Excel software)					

3.3. Regression Test

The details of WWR for each housing complex, along with the calculated mean satisfaction score, are presented in the following table (see Table 1). The scatter distribution (see Figure 1) between the WWR of each housing complex and corresponding resident satisfaction levels regarding the natural ventilation shows a non-linear pattern. Therefore, the study employed polynomial regression to examine the relationship between WWR and residents' satisfaction. A quadratic equation (2) was derived from the polynomial regression test, with a moderately strong coefficient of determination ($R^2 = 0.6494$). Using the primary dataset, the quadratic equation derived from the polynomial regression model can be expressed as:

$$y = -34.602x^2 + 23.053x - 2.865 \quad (2)$$

Where 'x' denotes the Window-to-Wall Ratio (WWR) and 'y' represents the mean satisfaction on a 0 to 1 scale (as per Cummins' %SM). The model has achieved an R^2 approximately equal to 65%, which indicates an acceptable level of explanatory power for the variance in residents' satisfaction with the independent variable (WWR). In this study, the WWR acts as an independent variable, as the residents' satisfaction levels depend upon the fenestration openings being provided to them.

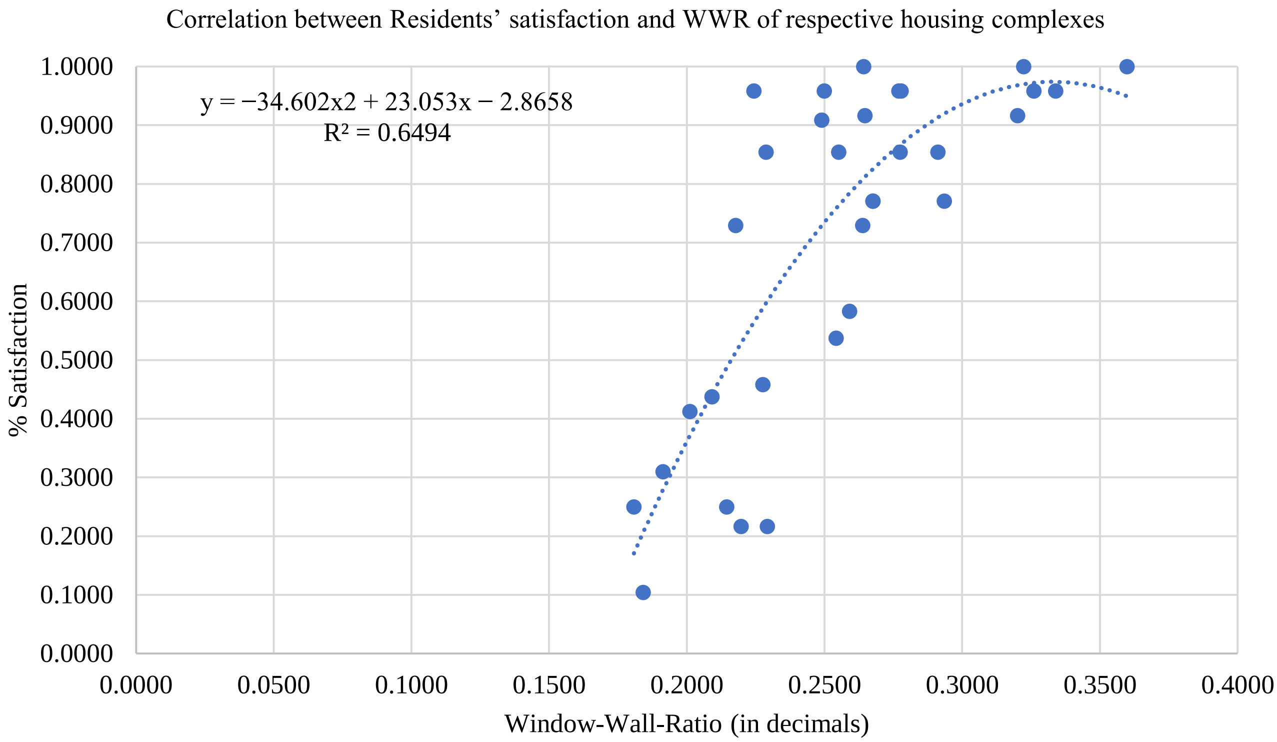

Fig. 1 Scatter plot between residents' satisfaction and WWR of respective housing complexes

3.4. Mathematical Optimisation

The regression equation expresses residents' satisfaction as a function of WWR, and this causal direction remains unchanged throughout the analysis. When the study calculates the parabola's vertex to determine the WWR that yields maximum satisfaction, it may appear as though the WWR is being solved based on satisfaction. However, this does not imply that satisfaction becomes the independent variable. Instead, this step involves analysing the mathematical properties of the regression curve to identify the point at which the predicted satisfaction reaches its maximum.

The x-coordinate of the vertex that maximises y for a downward-opening parabola can be written as follows:

$$x_{opt} = -\left(\frac{b}{2a}\right) \quad (3)$$

Where a = −34.602 and b = 23.053, the optimal x becomes 'x_{opt}';

$$x_{opt} = -\frac{23.053}{2 \times (-34.602)} = \frac{-23.053}{-69.204} \approx 0.3331 \quad (4)$$

Substituting x = 0.3331 in the regression model, the optimal y becomes 'y_{opt}';

$$y_{opt} = -34.602{x_{opt}}^2 + 23.053x_{opt} - 2.865 \quad (5)$$

$$= -3.839 + 7.676 + (-2.865) \approx 0.975 \quad (6)$$

The predicted mean satisfaction comes around 0.975. This indicates near-maximum perceived satisfaction with the corresponding WWR. To calculate the prediction interval (level of confidence) at 95%, the Standard Error of Estimate (SE = 0.1755) is considered. It represents the confidence band surrounding the predicted satisfaction curve. In other words, it means the range within which the future observations are likely to fall.

Table 2 shows how residents' ventilation satisfaction changes at different window-to-wall ratios. When the WWR is very low, around 18%, the predicted satisfaction is also low, and even the best-case scenario (at 95% confidence) the maximum reaches at ~50% (visualised in Figure 2). So small windows consistently result in poor ventilation comfort. Things start improving around 23.6% WWR; at this point, even though the average satisfaction isn't very high, there's at least a chance that some households could experience complete comfort if conditions are favourable.

At the higher end, around 36% WWR, satisfaction is already quite strong, and many households could potentially feel fully at ease. However, according to the math, the sweet spot is actually around 33.31% WWR; this is where the predicted satisfaction almost reaches its maximum.

Table 2. Predicted mean satisfaction and key WWR Values at 95% confidence intervals

Using the Vertex Formula	WWR	Predictive Mean Satisfaction % (in Decimals)	95% Confidence (Lower Range)	95% Confidence (Upper Range)
Minimum WWR	0.1808	0.172	0.000	0.523
Minimum Confidence WWR	0.2362	0.649	0.298	1.000
Maximum WWR	0.3598	0.950	0.599	1.000
Optimal WWR	0.3331	0.975	0.624	1.000
Source: Authors' calculations outcomes				

4. Results and Discussion

4.1. Results

The analysis essentially revealed that the relationship between WWR and residents' satisfaction with natural ventilation is not a straight line; it curves. The scatter plot made that pretty obvious, which is why a quadratic model was used instead of a simple linear one. The model fit the data reasonably well, explaining around 65% of the variation, and the resulting equation forms a downward-opening parabola. That shape indicates that satisfaction continues to rise as windows get larger, but only up to a point, after which the residents' satisfaction starts to taper off. A confidence band (see Figure 2) was also added using the 95% prediction interval, which helped highlight where satisfaction levels tend to fall in real situations. At very low WWR values, satisfaction remains poor no matter how favourable the conditions are. In contrast, mid-range WWR values allow much higher comfort and even complete satisfaction in some cases. Using the vertex formula, the optimal WWR is around 33%, where predicted satisfaction is almost at its maximum. The model also highlighted key thresholds: at roughly 18%, satisfaction is extremely low, and even the upper limit of '95% confidence level' remains weak, while around 24% WWR is the first point where complete satisfaction becomes possible for certain households. Satisfaction climbs steadily up to the optimum range of about 24% to 33%. Beyond that, the benefits start to drop off gently again, suggesting that excessive window area may introduce other issues that counteract the comfort gains.

The results indicate that WWR significantly influences resident satisfaction with natural ventilation in affordable housing units in Kolkata. This provides evidence-based guidance that WWR values below approximately 24% are establishing minimum design standards, indicating that they are consistently insufficient. Values between 24% and 33% provide increasingly reliable comfort, while beyond this, satisfaction drops. These findings provide an optimised facade design to enhance a quantitative foundation for thermal-air comfort in low-income residential settings.

4.2. Discussion

The present study identifies a practical range of Window-to-Wall Ratio (WWR) between approximately 24% and 33% that yields increasingly reliable ventilation comfort. In comparison, satisfaction decreases when the WWR exceeds approximately 33%.

4.2.1. Similar Findings

Several studies mentioned a WWR between 24% and 33%. Most of these studies say that the performance of daylight, cooling loads, and energy use is about the same in different climates and types of buildings. Krishnan (2018) found that in Indian high-rise residential buildings, 30% –35% WWR was suitable for warm-humid climates and 30% –40% for mixed climates. Gunjan Kumar *et al.* (2021) demonstrated that a Window-To-Wall Ratio (WWR) of 17% –37% enhanced energy savings in high-rise residential buildings in Kolkata. Raihan *et al.* (2022) indicated optimal performance at 30%–40% in residential and commercial structures within a hot climate (Hyderabad). Keshri and Dey (2023) determined that social housing was adequate in less than or equal to 38% of cases across various Indian climates. Chaturvedi *et al.* (2025) demonstrated that NZEBs in warm and composite climates typically utilise WWR ranging from 30% to 45%. Chanda and Biswas (2025) identified a WWR of 30%–36% as the optimal range across various vernacular climatic zones. Studies from other countries also back this study's findings. Pathirana *et al.* (2019) found that the WWR for tropical residential buildings in Sri Lanka ranged from 20% to 30%. Rana *et al.* (2022) found a range of 30%–40% for commercial structures in the warm-humid region of Bangladesh. Yi *et al.* (2024) reported a WWR efficacy of 30%–40% in warm-humid commercial and residential structures in Shanghai. These numbers fit within the target range of 24% to 33%.

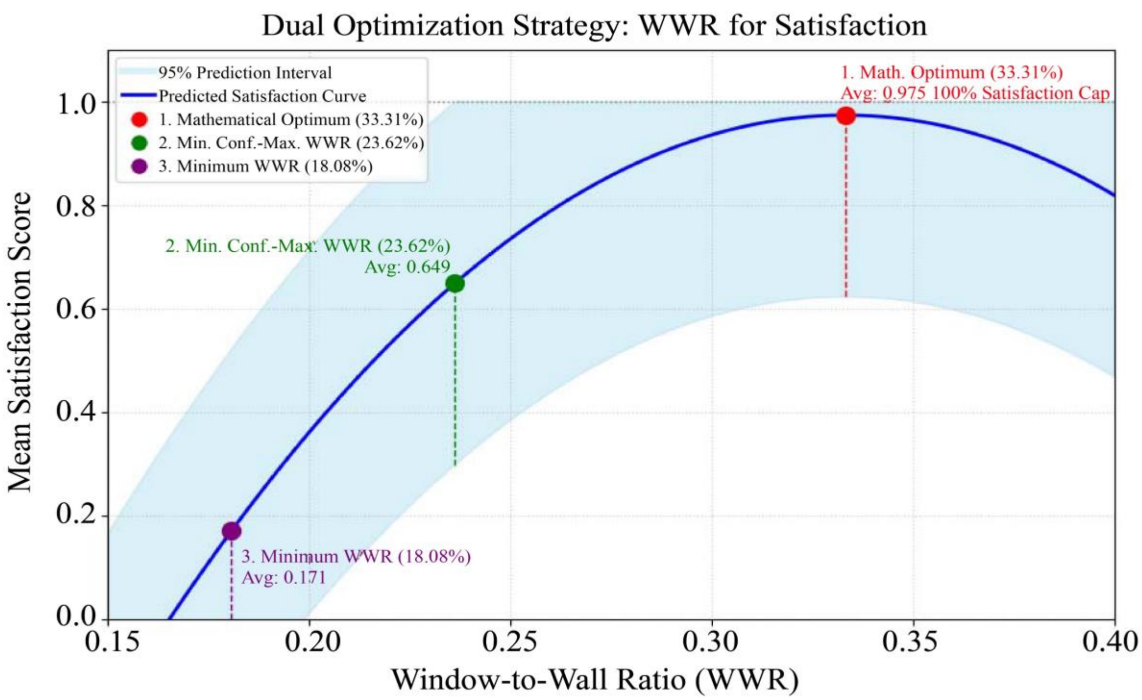

Fig. 2 Predicted residents' satisfaction curve with 95% prediction interval across WWR

4.2.2. Different Findings

Several studies suggest a WWR of less than 24%. Samanta et al. (2014) found that 10% –18% works best in tropical Asansol. Bose and Sarkar (2015) observed that reducing WWR to 10% –15% resulted in lower ventilation and comfort in low-rise tropical houses. Debnath and Bardhan (2016) saw low daylight with <20% WWR in high-rise Mumbai buildings, even though 50% gave more gains. Bhanware et al. (2019) stated that 15% is suitable for hot-humid residential buildings in seven Indian cities. Barman et al. (2020) reported 13.47% WWR in warm-humid Guwahati houses. They added that higher WWR needs stricter glazing control. Vishnubhotla et al. (2022) recommended 20% for South Indian hot-dry and warm-humid cities. Venkatesh et al. (2023) found that 20% works for multi-storey housing in the hot-humid climate of Kakinada. International studies also show low numbers.

Alibaba (2016) suggested 10% for hot Mediterranean offices in Cyprus. Feng et al. (2017) recommended 10–22.5% for cold to cool-temperate facades in China. Ziabari et al. (2019) said ≤20% on west facades in humid subtropical Iran. Alsehail et al. (2020) reported 10% – 20% for hot-dry Saudi Arabia. Bulus (2020) found 16% in tropical courtyard houses in Nigeria. Even more studies agree: Koohsari & Heidari (2021), Shrestha & Shakya (2022), Al-Yasiri et al. (2023), Cárdenas-Rangel et al. (2023), Hassieb et al. (2024), Kalathoki (2025), and Alwetaishi (2025) all found a similar range of 10% –22%. Basically, all these are clearly below the 24%–33% range mentioned elsewhere. Some studies suggested a WWR above 33%. Debnath and Bardhan (2016) saw significant daylight gains at 50% WWR in high-rise tropical buildings in Mumbai. Mohanta et al. (2021) suggested up to 40%, but with shading, for hot-humid commercial buildings in Kolkata. Saber (2021) recommended a WWR of 45–55% for semi-arid residential buildings in Iran. Wen et al.

(2017) reported 30% –70% reductions in energy use, depending on whether the climate was warm or cold, in Japanese commercial buildings. Shaeri et al. (2019) found 20% –30% on north facades, but higher ranges were okay for other sides in hot-humid and hot-dry offices in Iran. Chi et al. (2020) suggested a range of 30%–40% for traditional humid–temperate dwellings in China. Liu et al. (2021) and Sayadi et al. (2021) reported 30%–45% for mixed-climate buildings in China and Sweden. Rana et al. (2022) found a 40% upper range in commercial buildings in Bangladesh. Wu et al. (2025) suggested a 60% relative humidity level for hot-humid offices in Sanya. Xia et al. (2025) reported 40% for hot-humid schools in Guangzhou. Koohsari et al. (2024) suggested a range of 65% –95% for facade-specific energy savings in mixed climates in Iran.

Table 3. Optimal Window-to-Wall Ratio (WWR) for Maximum Satisfaction

Points	WWR Target	Predicted Satisfaction	Recommendation	Rationale & Context
1	33.31% (Mathematical Optimum)	97.5% (Peak Mean)	Primary target	Achieves the highest resident comfort and satisfaction with natural airflow.
2	23.62% (Minimum Confidence)	approx 65% (Mean)	Mandatory minimum	The lowest WWR that guarantees possible 100% satisfaction.
3	< 23.62%	Low (approx 17%)	Avoid	High risk of inadequate airflow, poor air circulation, and resident complaints (‘stuffiness’).

Source: Authors’ calculation outcomes

Most evidence clusters around 24%–33% WWR (see Table 3). This is especially true for mixed, warm-humid, and composite climates. Residential and commercial buildings also fit here, where both daylight and cooling loads are important. Below 24% usually targets hot, cooling-dominated climates. Above 33% goes more for daylight or winter heating benefits. The current study demonstrates a close relationship between WWR and residents’ perceived satisfaction with natural ventilation. The analysis suggests a moderate range, around 24%–33%, as the optimal sweet spot. It boosts airflow and thermal comfort, without the problems of too-small or too-large windows. The results also make it clear that ventilation is not just about window size. Climate, orientation, glazing type, and shading design also play significant roles. By optimising the WWR, the goal is to achieve better natural ventilation and comfort, especially in warm, humid, and composite climates.

4.2.3. Uniqueness in Methodology

The current study provides a more contextually responsive WWR through its post-occupancy evaluation approach. The previous studies primarily assessed ventilation potential through physical indicators such as airflow rates or thermal indicators. In contrast, the post-occupancy approach captures the perceived satisfaction with natural ventilation. This WWR reflects the lived performance by the users rather than the theoretical and analytical maximums.

5. Conclusion

This study addressed the research question: What is the optimal Window-to-Wall Ratio (WWR) that maximises homebuyers’ satisfaction with natural ventilation in affordable housing for a hot and humid city?

By integrating residents’ perceived satisfaction with measurable design parameters, the study directly answered this question. It was established that a moderate WWR range of approximately 24%-33% optimises natural ventilation while maintaining thermal comfort. Windows smaller or larger than this range were associated with lower occupant satisfaction, highlighting the importance of context-sensitive facade design in dense, cost-constrained affordable housing in Kolkata.

5.1. Contributions

The study offers newness in both context and methodology. Contextually, no prior research has specifically examined the relationship between optimal WWR and homebuyers’ perceived satisfaction in affordable housing, particularly with respect to natural ventilation. Methodologically, residents’ satisfaction was quantified using Cummin’s Percentage Scale Maximum (%SM), and a polynomial regression was applied to model the relationship between WWR and satisfaction. A predictive mathematical model, using the vertex formula of the quadratic equation derived from the regression, was then employed to identify the WWR that maximises perceived satisfaction. This approach addresses the gap in the existing field of knowledge between human-centric comfort evaluation and facade design.

5.2. Limitations and Future Scope

The research did not check residents’ satisfaction with WWR for different cardinal directions. Future work could explore this, seeing if north, south, east, or west-facing windows change airflow and comfort. Household interviews might have some social desirability bias. People could have responded the ‘expected’ way, as surveys were done at their homes. Future studies could use anonymous or sensor-based methods to get more unbiased responses. Survey timing missed night-shift workers or absent residents. Expanding the timing or using online surveys could include a wider group. Socio-demographic factors were not explicitly analysed in the current study. Adding age, income, family size, or lifestyle in future research might have different influences on perceived satisfaction with natural ventilation. The findings focus on privately developed affordable housing in Kolkata. At the same time, the method can be replicated in evaluating perceived satisfaction in residential as well as commercial properties in other cities across the globe.

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