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Evaluating the Impact of Jaali Façades on Building Energy Demand in Jaipur's Hot Semi-Arid Climate

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Abstract

The rising demand for cooling in hot semi-arid cities like Jaipur is putting increasing pressure on energy infrastructure and urban resilience. This study investigates the potential of Jaali, a traditional perforated screen used in Indian architecture, as a passive strategy to reduce energy demand in a contemporary office building through data-driven optimisation and computational analysis. Using detailed energy simulations in DesignBuilder, this research explores how variations in orientation, cavity depth, perforation ratio and screen thickness affect cooling performance during the summer months through a systematic parametric study generating 84 simulation configurations. The model is based on a 12-storey office building designed according to local energy codes. The results show that the optimal configuration differs by orientation. On the south façade, the optimal combination is a 100 mm Jaali with 20% perforation and a 1.5 m cavity, which delivers the best performance. The west façade performs best with a thicker 150 mm screen, the same 20% perforation ratio, and a 1.0 m cavity depth. On the east façade, the strongest performance is achieved with a 150 mm Jaali, 50% perforation, and a 1.5 m cavity, with cooling demand reduction of up to 8.71%. These findings demonstrate that traditional design elements, when optimised for modern use, can offer measurable energy savings through predictive modelling frameworks. More importantly, their widespread adoption could support urban cooling strategies, reduce peak electricity loads and contribute to sustainable development across rapidly growing cities in hot climates. The comprehensive dataset generated provides a foundation for future AI-enhanced building energy optimisation applications.

Keywords: building energy; Jaipur India; double screen; hot semi-arid climate; Jaali facade

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1. Introduction

Human activities such as burning fossil fuels produce greenhouse gases, which wrap around the earth like a blanket, trapping heat and raising temperatures, causing global warming [1]. The main contributing sectors include energy, industry, transport, buildings, and land use. To maintain thermal comfort in the built environment, buildings rely heavily on heating, ventilation, and air conditioning (HVAC) systems, which account for about 40% of global energy use and more than 30% of global CO_2 emissions [2]. Global energy demand in 2016 is projected to increase by 45% by 2050 [3]. In India, the building sector accounts for more than 30% of annual electricity consumption and is the second largest source of greenhouse gas emissions after industry [4]. The sector is projected to grow five-fold between 2005 and 2030, with corresponding increases in energy-intensive buildings and energy demand. Much of this growth is driven by rising air conditioning requirements,

which account for about 55% of electricity use in buildings. This pattern is especially visible in Rajasthan, where the extremely hot climate creates high cooling demand and rising temperatures lead to increased electricity consumption to maintain thermal comfort [5].

Office buildings are highly energy-intensive due to their operational requirements. A large share of this demand, about 68%, is consumed by HVAC systems [6]. Maintaining thermal comfort is, therefore, critical, not only for energy performance but also for workplace productivity. Studies show that work performance improves as temperatures rise to around 21 to 22 °C, peaks near 22 °C, and declines above 23 to 24 °C, with performance at 30 °C falling to about 91%, representing a 9% productivity loss [7]. Long operating hours, high occupancy, and equipment loads further increase office building energy use [6]. Incorporating passive design strategies is, therefore, essential to reduce HVAC dependence and improve overall energy efficiency.

The integration of passive design strategies with insulated building envelopes can reduce overall building energy use by 15 to 20%, with further reductions achieved through lower HVAC demand and improved lighting efficiency [8]. Among passive measures, solar shading is especially important in regions with intense solar radiation because it limits direct solar gains and reduces cooling loads [9]. Historically, hot and clear sky climates led to the development of effective passive cooling elements in traditional architecture, notably the Mashrabiya in the Middle East and the Jaali in the Indian subcontinent. In Indian buildings, Jaali screens provided shading, enhanced natural ventilation, and visual privacy [10], while both Jaali and Mashrabiya systems are recognised for combining shading and ventilation to improve thermal comfort in hot climates [11]. Their demonstrated performance supports the reinterpretation of Jaali designs in contemporary architecture to reduce cooling loads and overall energy consumption [12]. Jaipur's rapid urbanisation, rising cooling energy demand, exposure to extreme heat, urban heat island (UHI) intensity, and reliance on mechanical cooling highlight the need for scalable passive solutions at the city scale [13]. This study examines how Jaali-based design strategies can contribute to that transition, extending their relevance from individual buildings to the wider urban fabric. Recent advances in simulation workflows enable building-scale performance results to inform city-scale analysis by converting parametric simulation outputs into fast predictive surrogate models. These models approximate full energy simulations at a much higher speed, supporting large scenario testing and near real-time prediction. Accordingly, this paper identifies optimal Jaali configurations for a representative office building and demonstrates how the resulting parametric dataset can support machine learning-assisted urban energy analysis [14].

2. Objectives

This study investigates the potential of Jaali, a traditional perforated screen used in Indian architecture, as a passive design strategy to reduce cooling energy demand in office buildings located in hot semi-arid urban environments. The specific objectives are:

1. To evaluate the impact of façade orientation and Jaali configuration (including cavity depth and screen thickness) on cooling energy demand during the summer months.
2. To identify the optimal perforation ratio and geometric parameters that balance solar shading, daylight penetration, and overall energy efficiency.
3. To develop practical, simulation-based design guidelines that support architects and planners in integrating Jaali systems for climate-responsive buildings.
4. To assess the broader potential of Jaali applications in reducing aggregate urban cooling loads and advancing sustainable urban development in semi-arid cities such as Jaipur.

3. Background and Context

This section examines existing research on building energy consumption and the role of passive design strategies in mitigating climate impacts while improving indoor environmental quality. It also explores the architectural evolution and contemporary significance of the Jaali in hot climates. Reviewing key studies provides a foundation for understanding how Jaali-based design can contribute to reducing cooling loads and overall energy consumption.

3.1. Energy Consumption Patterns in Hot Climates

Buildings in hot climates consume increasing amounts of energy, primarily for cooling to maintain thermal comfort. Peak demand occurs during heat waves, when air conditioning (AC) systems account for most building energy use, surpassing lighting and equipment loads [15]. Commercial buildings, including offices, malls, and hospitals, exhibit particularly high cooling demand due to large floor areas, long operating hours, high occupancy, and extensive glazing [16]. UHI further amplifies temperatures and energy use [17]. Overall, cooling demand strongly shapes energy consumption patterns in hot climates, highlighting the need for passive design strategies to reduce reliance on mechanical systems.

3.2. Effect of Passive Cooling Strategies on Energy Demand in Hot Climates

Passive cooling enables heat exchange between building zones to achieve indoor temperatures lower than outdoor conditions [18]. Studies show that techniques such as solar shading and natural ventilation are among the most effective strategies for reducing energy use in hot climates. Shading is particularly valuable in warm and tropical regions. Le Corbusier's brise-soleil (sun-breaker) is a well-known example that blocks direct sunlight, lowering solar heat gain and maintaining cooler indoor environments. Its use in projects such as the Unité d'Habitation in Marseilles and the Capitol Complex in Chandigarh demonstrates how well-designed shading can reduce indoor temperatures by 2.5 to 4.5 °C and by 4.4 to 6.8 °C when combined with insulation and controlled ventilation, achieving 10 to 40% reductions in cooling energy use [9].

Windows are the primary source of heat gain due to their higher U-values compared with opaque envelope components, accounting for up to 60% of total building energy use in hot climates. Replacing single glazing with double glazing can halve cooling loads, while triple-glazed low-emissivity (Low-E) systems can further reduce solar heat gain. In hot arid regions, such as Saudi Arabia and the UAE, advanced glazing with low solar-gain coefficients can lower cooling energy by 35–40% [16]. In addition to high-performance glazing, adaptive façade solutions such as dynamic shading offer further potential for energy reduction. Studies show that these systems can achieve 27–48% reductions in cooling energy use in warm and tropical climates, offering a cost-effective alternative to expensive technologies such as electrochromic or triple glazing [19]. Overall, passive envelope strategies such as Jaali, shading systems, and high-performance façades can provide shading to windows and glazing, reducing city-wide building energy demand by 30–50%, contributing substantially to lower electricity use and carbon emissions while advancing urban sustainability goals.

3.3. Energy Challenges and Cooling Demand in the Region

In rapidly urbanising regions such as India, rising temperatures have intensified dependence on mechanical cooling. Projections suggest that, by 2050, cooling demand during extreme heat could exceed 75% of current annual electricity use, placing severe pressure on power grids [17]. India's commitment to the Sustainable Development Goals

(SDGs) forms the foundation of its ambition to become a developed nation by 2047. The Government of India has integrated the SDGs into national and regional development frameworks, prioritising sustainable and inclusive growth. The government has pledged to generate 40% of electricity from non-fossil fuel sources ahead of the 2030 target, reflecting strong progress toward SDG 7: Affordable and Clean Energy [20]. According to the India Cooling Action Plan, space cooling is expected to account for nearly 45% of peak electricity demand in the residential sector by 2037–38, underscoring the urgent need for sustainable cooling solutions [21].

Rajasthan, with its abundant solar radiation, has significant renewable energy potential [22]. It ranks second among Indian states in installed renewable capacity, producing 28,617 MW, of which 20.3% is derived from renewable sources [23]. However, the state's total electricity demand is projected to grow from 95,389 million units in 2021 to 182,504 million units by 2030, an annual increase of 7.4% [5]. This escalating demand places pressure on existing infrastructure, particularly as increased reliance on air conditioning in urban areas drives higher peak loads [23]. Jaipur, the capital of Rajasthan, experiences a pronounced UHI effect, particularly during nighttime. While rural areas heat up more rapidly during the day due to barren land exposure, urban surfaces retain heat after sunset, resulting in significantly warmer nighttime temperatures. This persistent heat limits opportunities for natural ventilation and increases dependence on mechanical cooling, particularly during the summer months [13].

To address these challenges, the Government of Rajasthan has adopted the Energy Conservation Building Code (ECBC), which promotes energy-efficient design in new construction. The ECBC encourages the use of passive cooling strategies, energy-efficient glazing, and shading devices to naturally reduce indoor temperatures and lower air conditioning demand [24]. Implementing these strategies in conjunction with renewable energy generation can help reduce overall electricity consumption, enhance energy resilience, and redirect saved energy towards other essential urban services and development priorities [23,24].

3.4. Climate of the Region

Jaipur, Rajasthan, is located in the semi-arid climatic zone and is expected to experience notable temperature changes under future climate scenarios. Projections indicate that Jaipur's mean annual temperature will rise from 26.5 °C during 2011–2040 to 27.8 °C by 2041–2070 and further to between 28.5 °C and 29.1 °C by 2071–2100 [25]. Minimum temperatures are projected to increase by 0.23 °C to 1.42 °C across southeast to northwest Rajasthan during 2011–2040, leading to warmer nights and reduced opportunities for natural cooling. Maximum temperatures could rise by 2.43 °C to 4.27 °C by the end of the century, intensifying summer heat and thermal stress [25]. This temperature rise is influenced by Jaipur's lower elevation, proximity to the Thar Desert of Rajasthan, and the overall global warming trends [25].

The frequency of heatwaves, warm days, and tropical nights is expected to increase, while the number of cooler days will decline, indicating reduced diurnal variability and prolonged periods of high temperature [25]. By 2071–2100, Jaipur could experience up to 39 additional extreme heat days per year. These projected changes pose critical challenges for urban sustainability, including greater heat stress, water scarcity, and reduced livability. To address these risks, adaptive measures such as improved passive cooling design, enhanced water management, and climate-resilient urban planning are essential. As Jaipur continues to expand, embedding climate adaptation within urban development and building design will be vital for ensuring long-term thermal comfort and resilience [25].

3.5. Jaali as a Traditional Architectural Element

Mashrabiya and Jaali are iconic elements of Islamic and Indo-Islamic architecture, renowned for their aesthetic beauty and climatic functionality. Both serve as decorative perforated screens that regulate light, airflow, and privacy. Although known by different names across regions, their underlying principles remain similar. In India, the Jaali typically refers to intricately carved stone or wooden lattice screens, while in the Middle East, particularly Egypt and the Arabian Peninsula, the Mashrabiya denotes a projecting wooden screen on building façades as shown in Figure 1. Over time, these elements have evolved in response to cultural, technological, and environmental changes, maintaining their relevance in contemporary architectural practice [26].

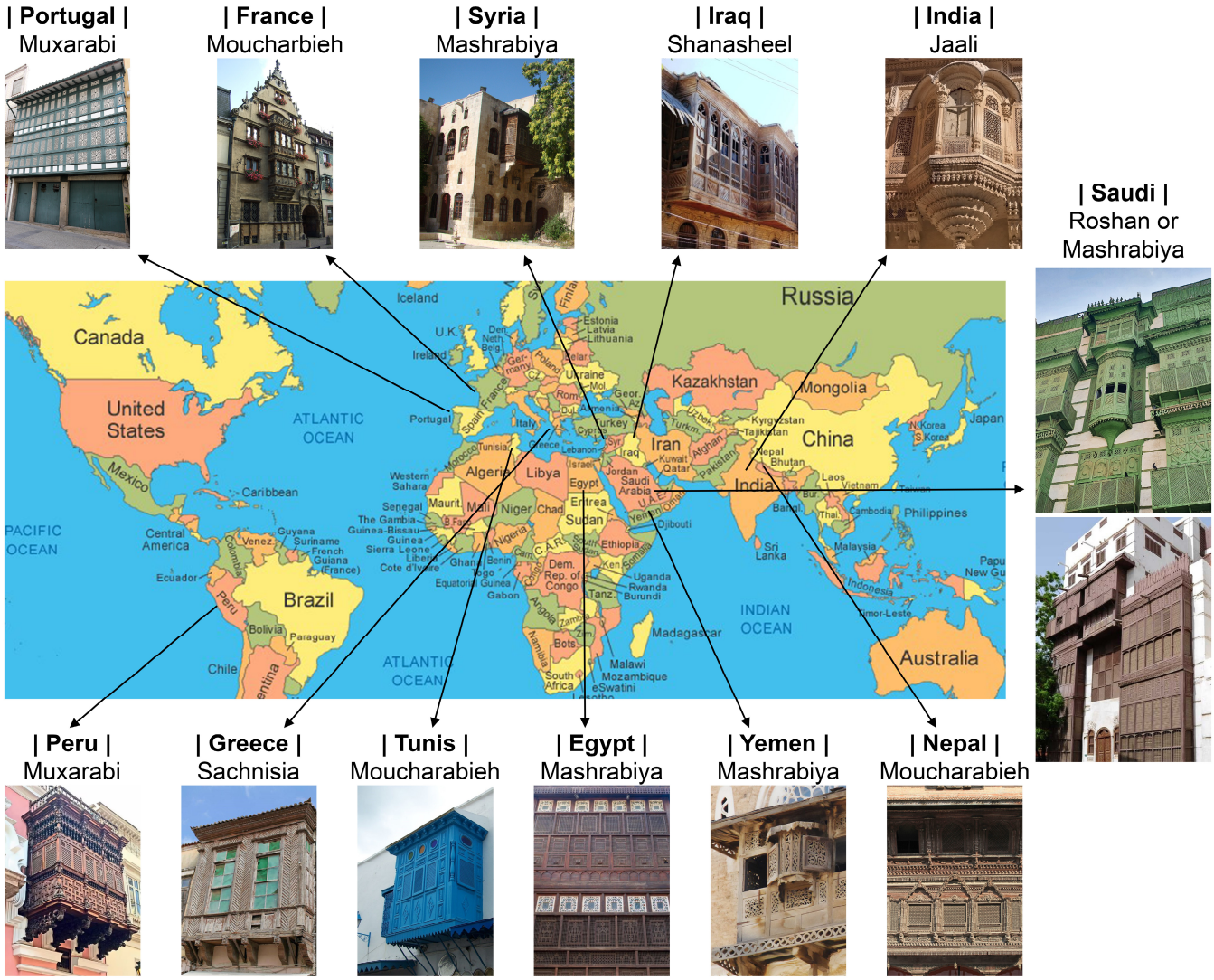


Figure 1. Use of Jaali in different parts of the world with their local names. The Mashrabiya originated in the Abbasid period of medieval Islamic civilisation (750–1258 CE), initially serving as screened spaces for cooling water containers through evaporation. Gradually, this practical feature evolved into an architectural device providing shading, ventilation, and privacy in both residential and public buildings [27]. The term derives from the Arabic sharab ("to drink") or mashrafiya ("to observe"), reflecting its dual role in cooling and visual screening [27].

The origins of the Jaali can be traced to early Indian architecture, evident in stone carvings at the Ajanta Caves and the fortified towns of the Harappan civilisation. Initially simple in design, Jaali screens became increasingly elaborate during the Mughal era, when

geometric and floral motifs were integrated into palaces, mosques, and mausoleums. These designs not only enhanced aesthetic quality but also controlled solar penetration and improved ventilation [26].

3.6. Evolution of Jaali

Jaali screens are integral to Indo-Islamic architecture, combining artistry with climatic functionality. Their perforated geometry filters light, promotes ventilation, and maintains privacy while enriching interior ambience through the play of shadow and daylight. The repetitive geometric patterns also reflect symbolic notions of unity and infinity in Islamic art. Beyond their aesthetic value, Jaali screens enhance passive cooling by accelerating airflow and blocking direct solar radiation [26]. Similarly, the Mashrabiya in Middle Eastern architecture integrates artistic and environmental design. Its projecting lattice structure promotes ventilation, limits solar penetration, and ensures visual privacy. Traditionally made from wood, modern Mashrabiyas now employ advanced materials and kinetic systems, extending their application to high-rise façades and contemporary commercial buildings. The differences between a Jaali and a Mashrabiya are summarised in Table 1. This evolution illustrates their adaptability and continued relevance as sustainable façade systems [27].

Table 1. Distinction between Jaali and Mashrabiya [26,27].

Feature	Jaali	Mashrabiya
Origin	Indian Subcontinent	Middle East
Material	Stone/Concrete	Wood
Function	Shading + Ventilation	Shading + Privacy
Depth	Often Flush/Perforated	Often Projected Box

3.7. Impact of Jaali

3.7.1. Shading and Solar Heat Gain Reduction

Solar radiation is the primary driver of cooling demand in hot arid climates. Perforated solar screens reduce heat gain by filtering direct sunlight and lowering building energy use [28]. Their performance depends on geometric parameters such as cavity depth, orientation, and perforation ratio, as shown in studies of daylight availability in desert residential buildings [29]. Evidence from desert buildings in Egypt's Kharga Oasis shows that optimised screens can achieve energy savings of up to 30%, particularly on south- and west-facing façades, with perforation ratios of 80 to 90% and depth-to-opening ratios close to 1 to 1 [28]. Related studies of double-skin façades incorporating Mashrabiya or Jaali elements report peak solar heat gain reductions of up to 78%, with corresponding decreases in air conditioning demand [30]. Simulation results further indicate that Jaali screens with 30 to 50% perforation on south façades lower indoor temperatures by creating a shaded air buffer that enhances ventilation and reduces mechanical cooling loads [31].

3.7.2. Thermal Mass and Heat Transfer

The thermal behaviour of perforated double façades depends strongly on material and cavity configuration. Research comparing galvanised steel and aluminium panels found that aluminium's higher reflectivity and conductivity make it more suitable for hot climates, as it rapidly dissipates absorbed heat [32]. Cavity width also influences energy efficiency: wider air gaps (0.05–0.30 m) reduce heat transfer and cooling loads, while optimal perforation rates (around 25%) balance daylighting and shading in hot arid regions

such as Seville. When reflective materials such as polished aluminium are used, façades can reduce cooling demand by over 30% while maintaining adequate daylight [32].

3.7.3. Overall Energy Performance

Studies in Saudi Arabia highlight the environmental and cultural importance of retaining Mashrabiya in modern design. Simulations showed that traditional Mashrabiya systems can lower operating temperatures by 14%, cut peak solar gain by nearly 78%, and reduce cooling loads by 5–6% while improving natural lighting efficiency by over 35% [33]. In Doha, screens with 30% perforation achieved energy reductions up to 45%, while in hot humid cities such as Lahore, higher perforation ratios (50%) proved more effective [34]. Double-skin façade studies indicate that cavity depths around 0.9 m and south-facing orientations provide the greatest cooling benefits, reducing annual cooling energy by about 31% [35]. Parametric studies of Jaali geometry show that a solid-to-void ratio of 70:30 and a 100 mm screen depth achieve the best balance between daylight availability and thermal comfort [10].

3.8. Computational Methods in Building Energy Optimisation

Recent advances in machine learning and computational modelling have enhanced the predictive capability of building energy simulations. Deep learning models, such as convolutional and long short-term memory networks, can forecast hourly energy demand with over 20% greater accuracy than traditional statistical methods [36]. Parametric optimisation frameworks using algorithms like genetic or particle-swarm optimisation can explore thousands of façade configurations to identify those offering the best energy performance [37]. These approaches can directly integrate Jaali parameters such as perforation ratio, depth, and orientation to develop predictive models that optimise design for specific climatic contexts.

3.9. Modern Interpretation of Mashrabiya in Architecture—Al Bahr Towers

The Al Bahr Towers in Abu Dhabi exemplify the modern adaptation of Mashrabiya for high-performance façades. Each tower employs a responsive shading system of over 1000 movable panels that adjust their geometry according to the sun's position, reducing glare and solar gain while maintaining uniform daylight levels [38,39]. The adaptive screens maintain interior illuminance between 250 and 2000 lux, reducing dependence on artificial lighting [12]. Field measurements showed up to a 20% reduction in peak cooling demand and a 50% decrease in solar gains, leading to an annual saving of approximately 1750 tonnes of CO_2 emissions. The optimised façade also lowered material use by 20% and reduced the required cooling plant capacity by 15%, demonstrating the potential of dynamic Mashrabiya systems in achieving sustainable design outcomes in hot desert climates [12].

4. Materials and Methods

This study evaluates how alternative Jaali configurations, identified through the literature, reduce cooling energy demand during the summer months in a hot semi-arid Indian context. A simulation-based approach was used to quantify the effect of façade orientation, cavity depth, perforation ratio, and screen thickness on cooling energy consumption. An advanced building energy modelling tool provided hourly calculations for the selected climate and building typology. Figure 2 summarises the overall workflow.

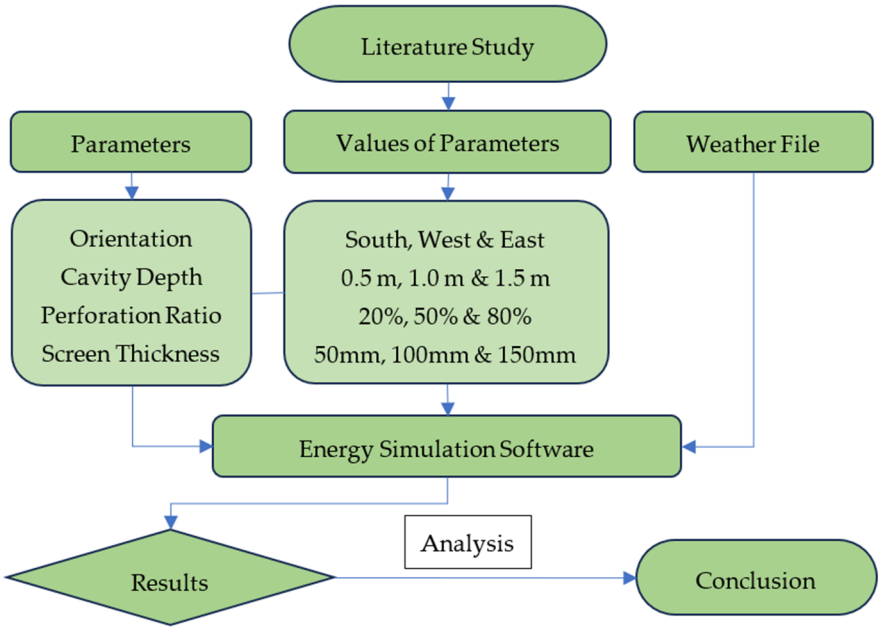


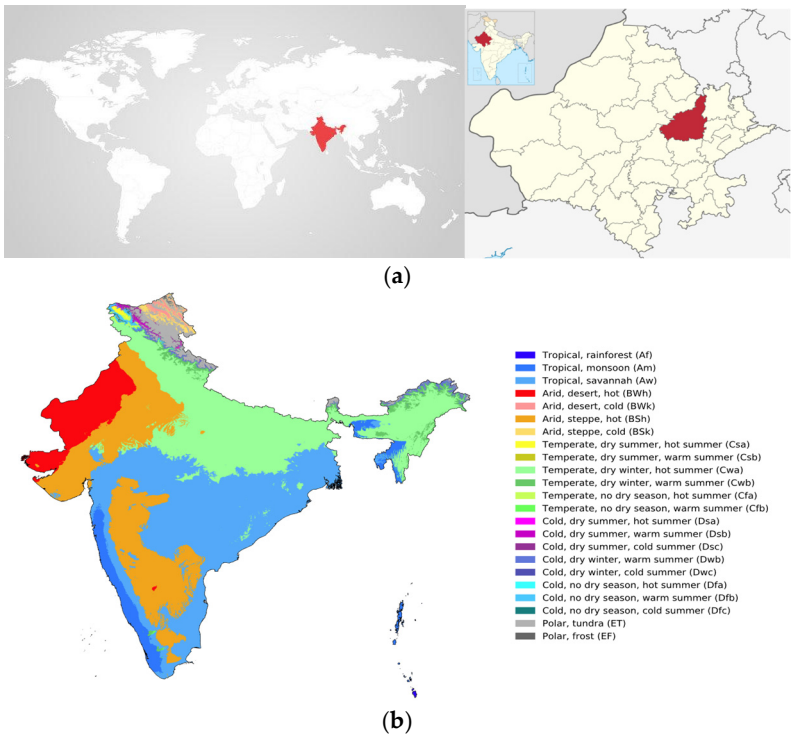
Figure 2. The overall workflow.

4.1. Location and Context

The case study is Jaipur, Rajasthan, located on the edge of the Thar Desert in north-western India (Figure 3a) and classified as hot semi-arid (BSh) under Köppen–Geiger. Summers are characterised by high air temperatures, intense solar radiation, and low relative humidity [40] (Figure 3b). Jaipur's heritage architecture makes extensive use of *Jaali* screens for shading, ventilation enhancement, and privacy, which supports their selection for modern reinterpretation in this climate [41]. Frequent summer electricity shortfalls exacerbate indoor overheating, which increases the value of passive measures that can lower cooling loads [42]. Local policy, including the Energy Conservation Building Code, promotes passive design and energy efficiency, making Jaipur an ideal test bed for guideline development [4]. India, being situated in the equatorial sun belt, receives a significant amount of solar energy. According to the Indian Meteorological Department, most regions experience clear, sunny conditions for 250 to 300 days annually, with average solar radiation ranging between 5 and 7 kWh/m^2, which is adequate for solar power installations. The country's annual global solar radiation ranges from 1600 to 2200 kWh/m^2, with Rajasthan receiving the highest levels. Specifically, Jaipur receives an average of 5.6 kWh/m^2 over approximately 325 days each year [43]. Prior evidence supports this decision, since perforated screens on north façades tend to influence electric lighting rather than cooling demand [28]. Due to it, the analysis excludes the north orientation and focuses on the south, west, and east.

Buildings in the hot semi-arid (BSh) region require window shading for about 35% of the time annually, and the natural ventilation is generally ineffective for summer comfort, which shows a need for cooling with dehumidification. This justifies the use of an external Jaali as a double-skin façade to deliver shading to reduce the effect of heat gain [44].

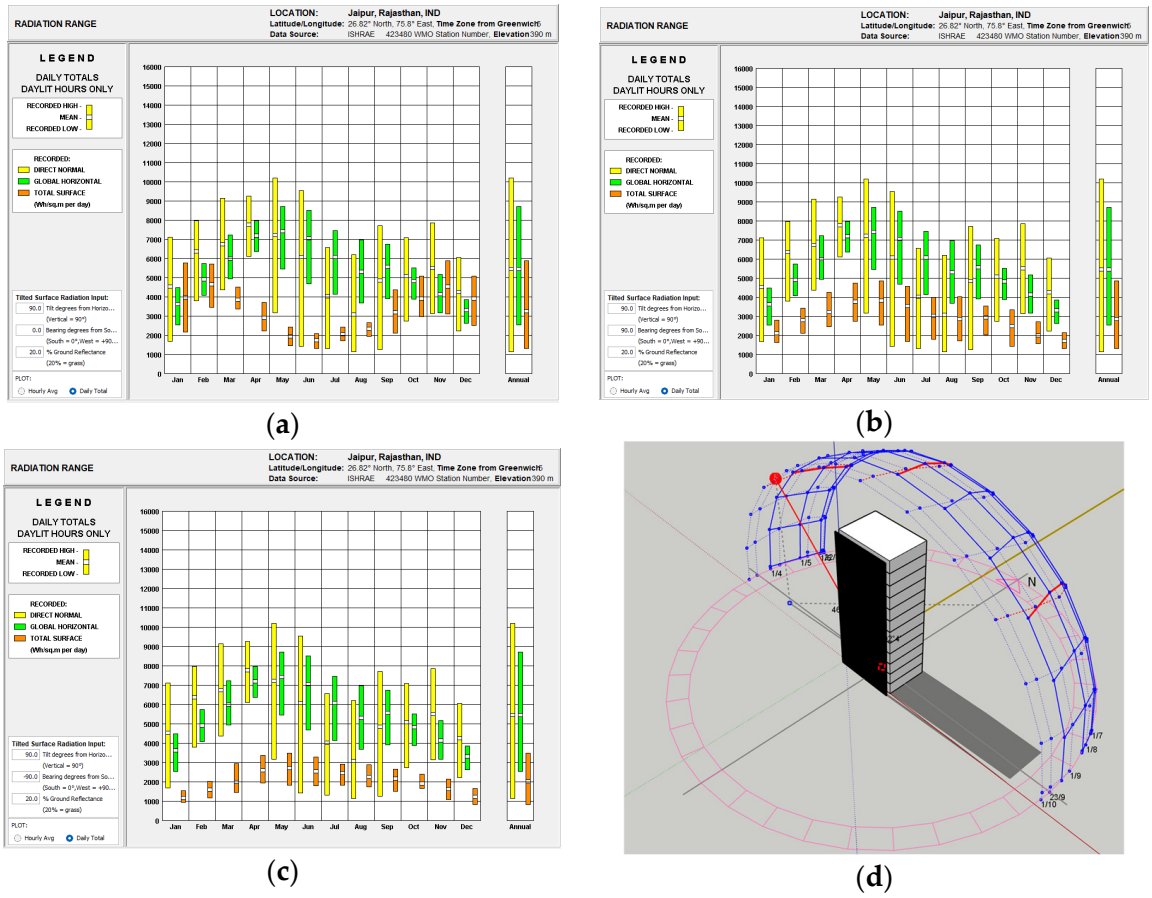
Figure 4 shows the solar radiation across the south orientation. In the summer months, the radiation was observed to be the highest, which stayed above 3000 Wh/m^2. Across the west orientation, the radiation was again observed to be above 3000 Wh/m^2, except in the month of October. The solar radiation across the east orientation was observed to be moderate between 2000 and 3000 Wh/m^2.



(**a**)

(**b**)

Figure 3. (**a**) Geographical location of Jaipur, Rajasthan, India on the world map and (**b**) India as per Köppen–Geiger Classification 1980–2016 [40].



(**a**) (**b**)

(**c**) (**d**)

Figure 4. (**a**) Solar radiation on south, (**b**) on west and (**c**) on east (Climate Consultant 6.0); (**d**) Solar angle on the building during the summer months (SketchUp 2023).

4.2. Building Model Specification

To test the façade parameter space under realistic regulatory constraints, a prototypical office building was modelled according to local bylaws. The scheme represents a freestanding twelve-storey office building with an overall height of 36 m on a site larger than 2500 square metres, featuring an 18 m road width, 40% ground coverage, and a built-up area ratio of 2 (Figure 5a) [45]. Each floor is 3 m high. The plan dimensions are 15 m by 10 m, with the principal façade oriented south. Interior spaces are arranged on a 5 by 5 m grid. Jaali screens are applied to windows on the south, west, and east façades, one orientation at a time.

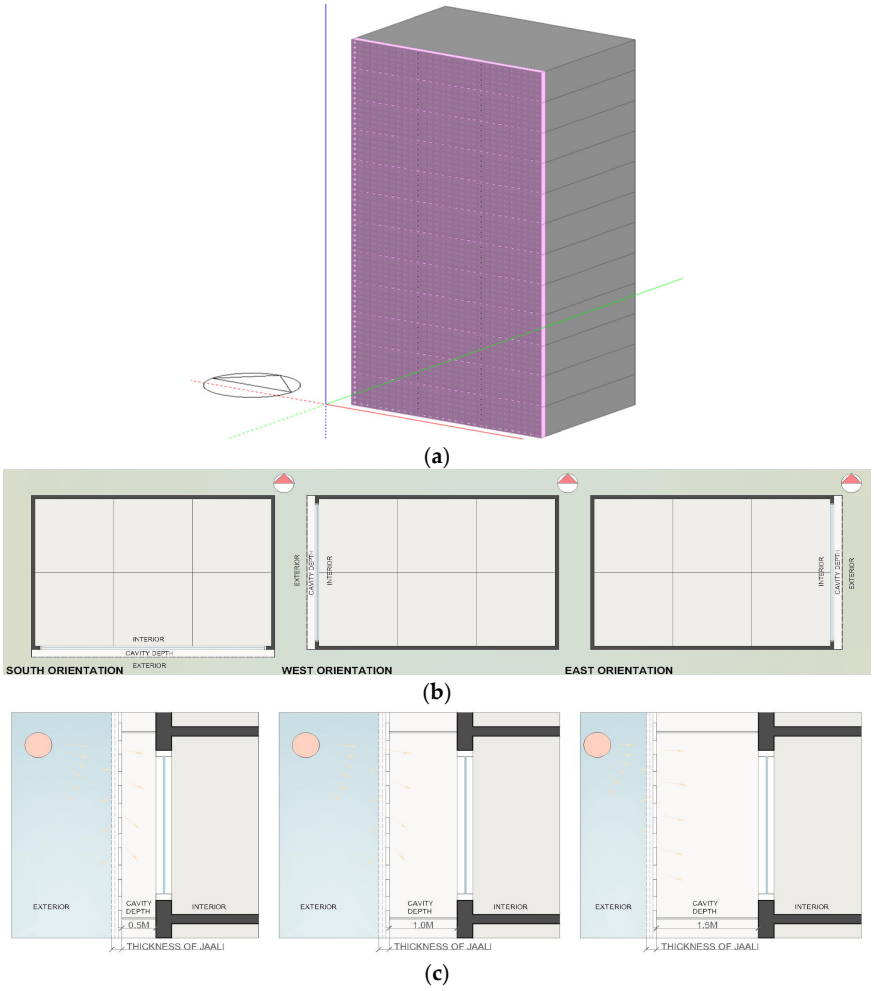


Figure 5. (**a**) Jaali in south orientation of building model (Design Builder v7.2.0.032); (**b**) plan depicting the orientation of the opening with Jaali (AutoCAD LT 2015); (**c**) section showing Jaali thickness and cavity depth between Jaali and the glazing. (AutoCAD LT 2015).

To magnify façade effects in a controlled manner, the window-to-wall ratio on the tested façade is set to 90%, while the remaining façades have opaque walls. This isolates the impact of the screen on a single orientation [46,47]. Glazing complies with ECBC guidance and uses double glazing with a U-value of 5.1 W/m^2 K, comprising 6 mm blue exterior glass, a 6 mm air gap, and 6 mm clear interior glass [4].

The screen is modelled as a reusable component within the simulation platform to allow systematic variation. Contemporary Jaali is often constructed in concrete, so the baseline material is a grey brushed flat concrete with thermal conductivity of 0.38 W/m^2 K [48]. Thickness and perforation are parameterised. Base cases on each orientation omit the screen.

Opaque envelope constructions reflect regional practice. External walls use 12.5 mm cement plaster, 225 mm brickwork, and 12.5 mm internal plaster for a U-value of 2.13 W per square metre Kelvin. The roof consists of 100 mm reinforced concrete, 50 mm foam concrete, and waterproofing, with a U-value of 1.08 W/m^2 K [4]. Infiltration is set at 5 air changes per hour at 50 pascals, consistent with air-conditioned offices [49]. The HVAC system is a split air conditioning arrangement typical of the region [42,50].

Lighting employs an LED template with a power density of 5.0 W/m^2 at 100 lux and an ECBC office schedule; lighting controls are disabled to isolate cooling effects. Occupancy is 0.110 people per square metre, and equipment density is 11.77 W/m^2, both aligned with ECBC schedules [4].

4.3. Simulation Parameters for Solar Screen

Three façade orientations are analysed, namely south, west, and east, with the screen applied to one orientation per run (Figure 5b). The cavity between screen and glazing varies at 0.5 metre, 1.0 metre, and 1.5 metre (Figure 5c) to capture shading depth and buffer-zone effects that influence heat dissipation and sol-air temperature [31,51]. The perforation ratio, defined as the open-area fraction, is set at 20%, 50%, and 80%, since openness governs direct solar transmission and, therefore, cooling demand [28] (Figure 6). Screen thickness varies at 50 mm, 100 mm, and 150 mm to reflect optical edge depth and potential thermal mass effects [28].

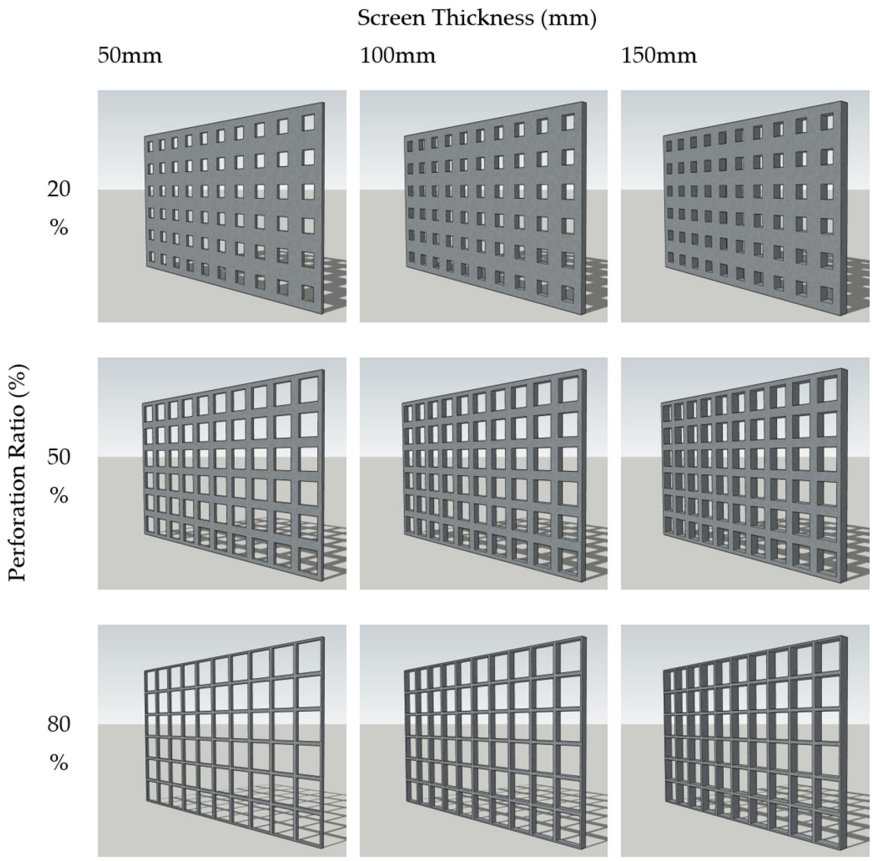


Figure 6. Illustration of Jaali thickness and perforation ratio (SketchUp 2023).

4.4. Simulation Setup

The present study is based on dynamic thermal simulations using DesignBuilder v7.2.0.032, which uses EnergyPlus 9.4.0 and has been extensively validated against experimental data in previous building performance studies.

It performs the hourly simulations. The tool calculates energy use against the local climate using a typical meteorological year weather file and evaluates cooling loads while maintaining ASHRAE 55 comfort targets [52]. The primary performance metric is site energy consumption per square metre for the summer months, with a focus on cooling energy. The analysis intentionally excludes lighting energy interactions to isolate cooling behaviour, following the emphasis in comparable façade studies [28]. Simulations cover April through October, which represent the months with the highest cooling demand [13]. The weather file is Jaipur, Rajasthan, IND, ISHRAE, World Meteorological Organisation station 423480, typical meteorological year.

4.5. Simulation Procedure

The procedure involves an objective to conduct a comparative assessment of façade configurations under consistent boundary conditions. A full factorial set of parameter combinations was executed for each of the three orientations. The parameters are cavity depth at 0.5 m, 1.0 m, and 1.5 m; perforation ratio at 20%, 50%, and 80%; and screen thickness at 50 mm, 100 mm, and 150 mm. Together with base cases without screens, this produced 84 simulations. Each run yielded summer site energy and cooling load results. The resulting matrix enables clear attribution of energy effects to each parameter and provides a coherent dataset for subsequent predictive modelling. By treating the simulation outputs as structured data, this study creates a foundation for training surrogate models that predict cooling performance from specific Jaali parameters and orientations.

4.6. Data Analysis

The analysis proceeds in four steps. First, it quantifies the effect of orientation on cooling energy consumption for the base case and the screened cases. Second, it evaluates how increasing the cavity depth alters cooling energy at constant perforation and thickness. Third, it examines the role of the perforation ratio on transmitted solar gains and the resulting cooling energy. Fourth, it assesses the incremental influence of screen thickness once depth and perforation are set. The objective is to identify orientation-specific configurations that minimise cooling energy in Jaipur's semi-arid climate and to translate these findings into design guidance for office buildings.

4.7. Study Limitations

The present study is based on dynamic thermal simulations using the EnergyPlus simulation engine implemented through DesignBuilder. EnergyPlus has been extensively validated against experimental building performance data and is widely used for evaluating passive design strategies [53]. The objective of this study was to conduct a comparative assessment of different Jaali façade configurations under consistent parameters rather than to predict absolute field performance. Nevertheless, future studies should incorporate experimental monitoring of cavity air temperature, airflow patterns, and façade surface temperatures to further validate the simulated results under real climatic conditions.

5. Results

5.1. Energy Consumption of the Base Case

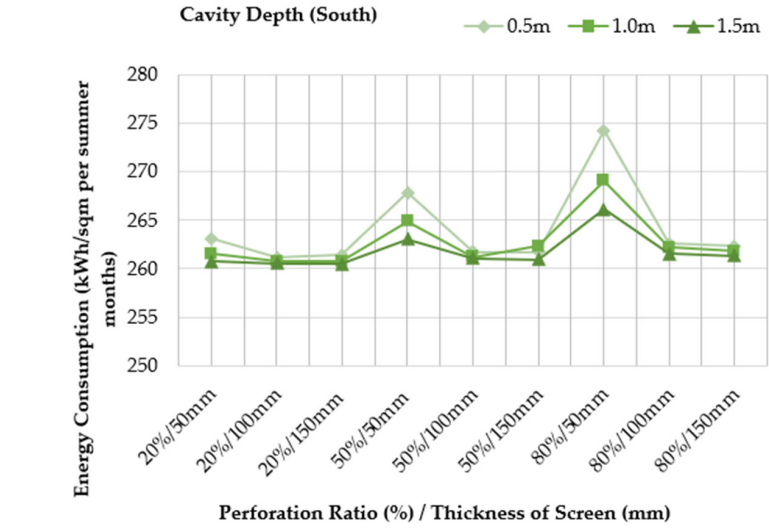
In the base-case scenario, where no Jaali screen was applied to the glazing, the results serve as the benchmark for comparing the effect of Jaali integration on cooling energy demand. The simulated cooling energy consumption during the summer months varied across orientations, recording 283.06 kWh/m^2 for the south façade, 279.28 kWh/m^2 for the west façade, and 281.32 kWh/m^2 for the east façade. The south façade exhibited the

highest cooling energy consumption, consistent with its greater solar exposure throughout the day.

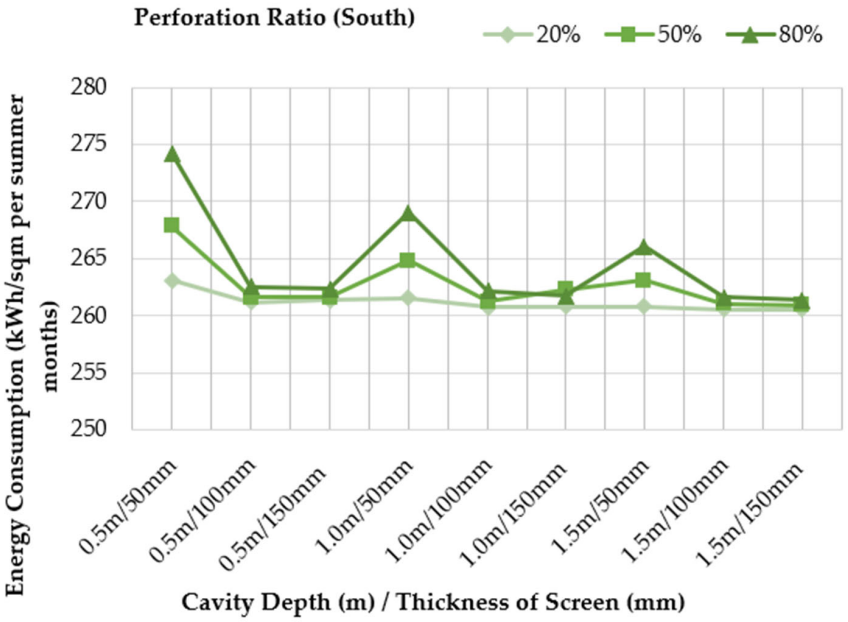
5.2. Energy Consumption of the Alternative Screen Configuration

5.2.1. South Orientation

The effect of cavity depth, perforation ratio, and screen thickness on cooling energy consumption for the south façade is illustrated in Figure 7. The results show a consistent reduction in energy consumption as the cavity depth increased from 0.5 m to 1.5 m, with the most notable improvement occurring between 0.5 m and 1.0 m (Figure 7a). At a cavity depth of 0.5 m, the energy consumption ranged from 261.17 to 274.32 kWh/m^2, with the lowest value achieved at a 20% perforation ratio. Increasing the cavity to 1.0 m further reduced the energy demand, with values ranging from 260.74 to 269.08 kWh/m^2. At 1.5 m, the range narrowed to 260.51–266.12 kWh/m^2, indicating a marginal gain compared to the 1.0 m cavity.

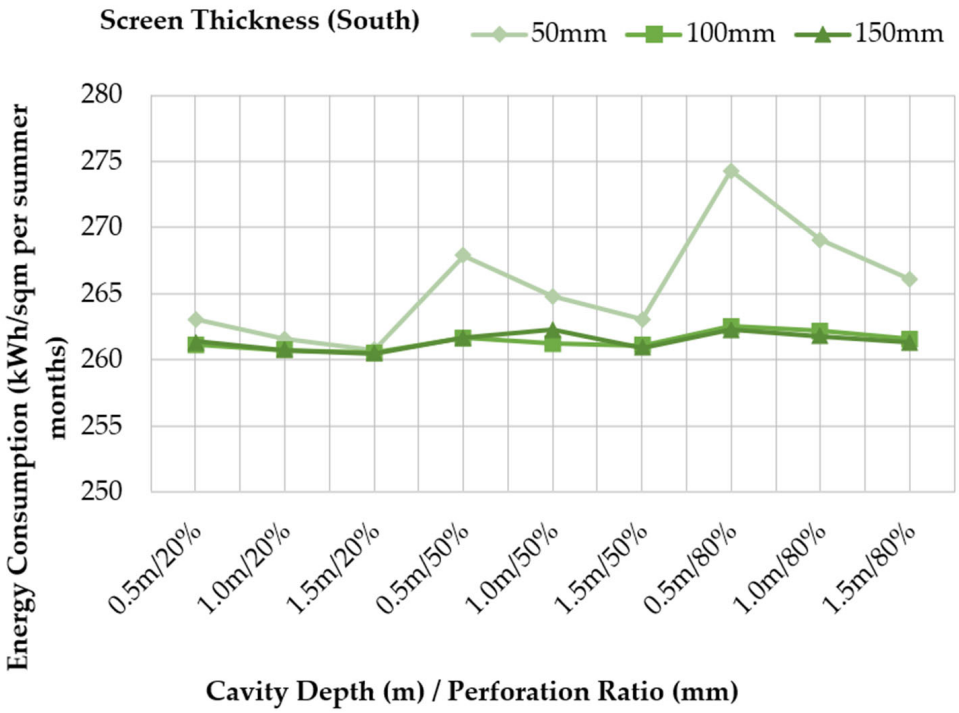


(**a**)



(**b**)

Figure 7. *Cont.*



(**c**)

Figure 7. Impact on energy consumption in south due to (**a**) cavity depth, (**b**) perforation ratio and (**c**) screen thickness.

The influence of perforation ratio is shown in Figure 7b, where energy consumption increases with larger openings. The 20% perforation ratio consistently produced the lowest energy use, while 80% perforation resulted in the highest consumption across all depths and thicknesses. Figure 7c illustrates the effect of screen thickness, revealing that thicker Jaali screens (100–150 mm) generally resulted in lower energy use compared to the 50 mm screen. The differences between 100 mm and 150 mm screens were minor, suggesting stable performance beyond 100 mm thickness.

5.2.2. West Orientation

The cooling energy consumption patterns for the west façade are presented in Figure 8. Across all configurations, variations were minor compared with the south orientation. At 0.5 m cavity depth, energy use ranged between 257.19 and 257.29 kWh/m^2, decreasing slightly to 257.02–257.11 kWh/m^2 at 1.0 m, and stabilising at 257.05–257.31 kWh/m^2 at 1.5 m. The general trend, shown in Figure 8a, indicates that increasing cavity depth reduces energy use slightly up to 1.0 m, with minimal change beyond this point.

The influence of the perforation ratio for the west façade, depicted in Figure 8b, follows a similar pattern to the south façade. The 20% perforation ratio resulted in the lowest consumption, 50% showed moderate values, and 80% resulted in the highest. The effect of screen thickness, shown in Figure 8c, demonstrates that energy consumption decreases as the screen thickness increases from 50 mm to 150 mm, with the thickest screen achieving marginally better results.

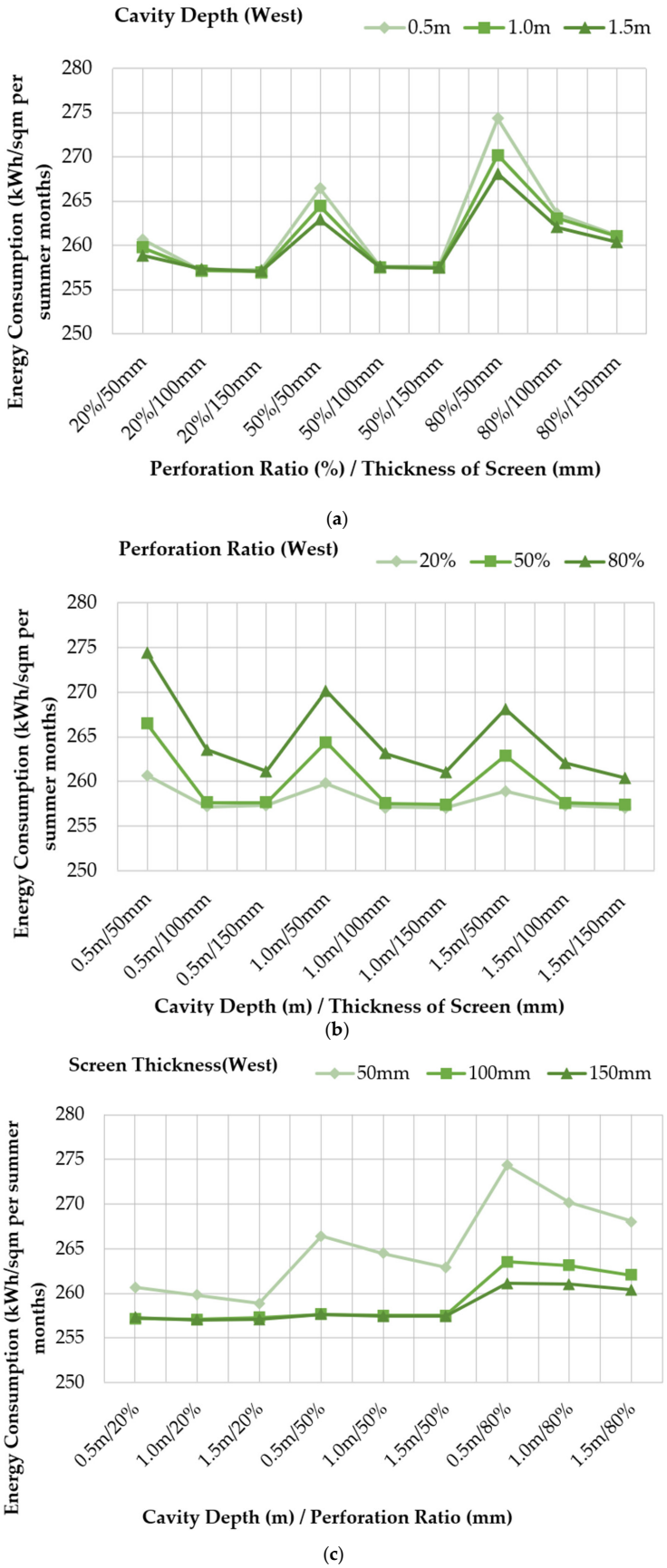
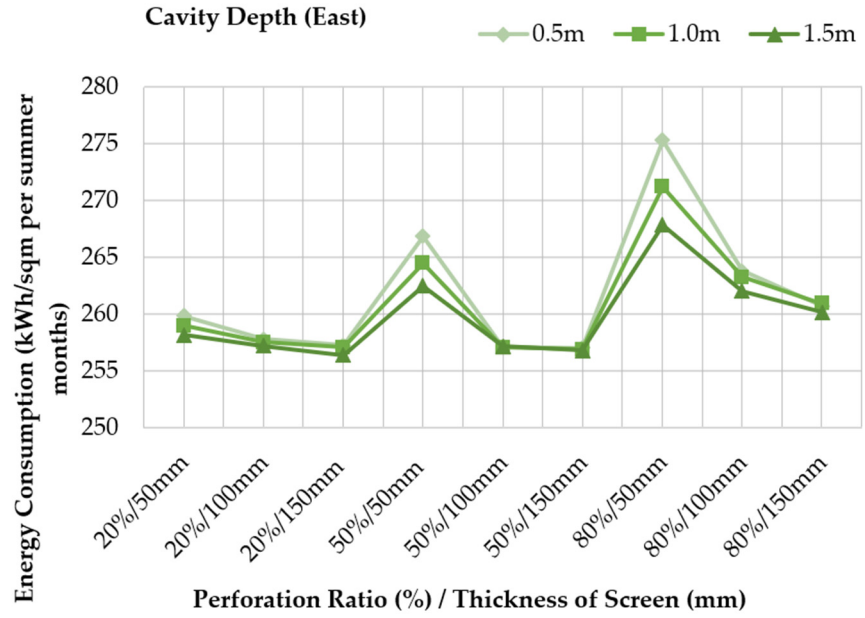


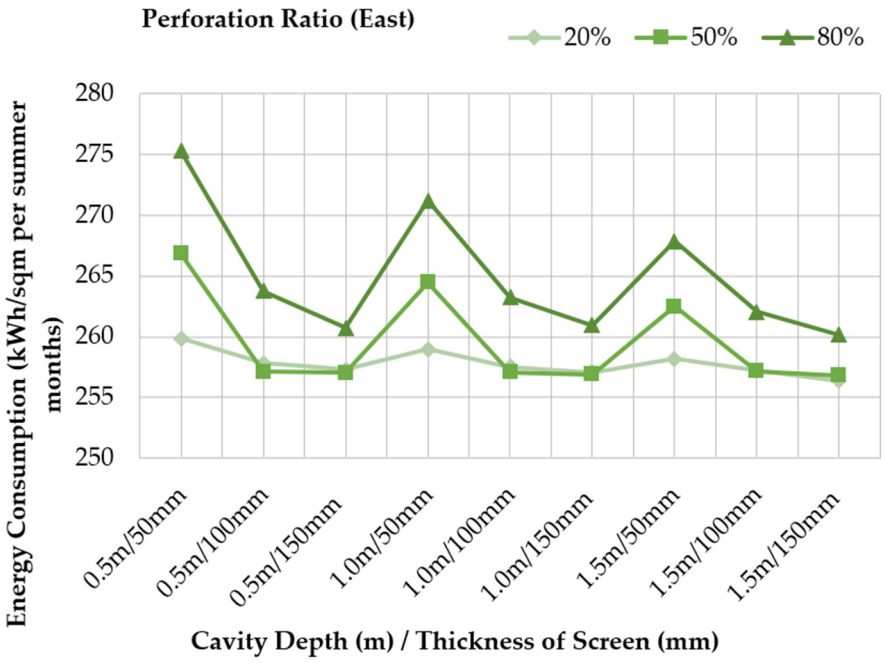
Figure 8. Impact on energy consumption in the west due to (**a**) cavity depth, (**b**) perforation ratio and (**c**) screen thickness.

5.2.3. East Orientation

The results for the east façade, shown in Figure 9, indicate a wider range of values across different configurations. At 0.5 m cavity depth, energy consumption ranged from 275.31 to 257.05 kWh/m^2, reducing to 271.22–256.91 kWh/m^2 at 1.0 m, and further to 267.86–256.38 kWh/m^2 at 1.5 m. The trend for the reduction is clear in Figure 9a, where the most notable improvement occurs between 0.5 m and 1.0 m, with only slight gains beyond 1.0 m.

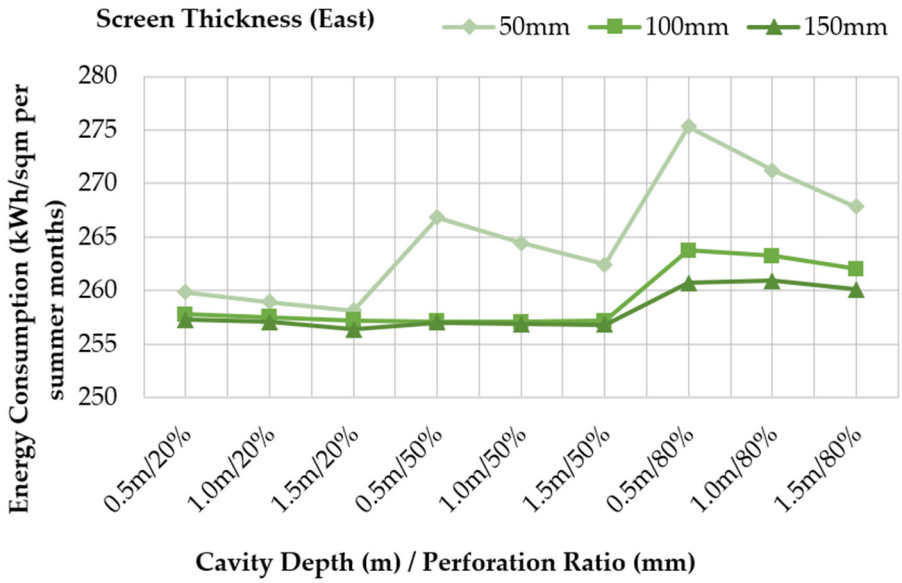


(**a**)



(**b**)

Figure 9. *Cont.*



(**c**)

Figure 9. Impact on energy consumption in the east due to (**a**) cavity depth, (**b**) perforation ratio and (**c**) screen thickness.

The effect of perforation ratio, shown in Figure 9b, reveals that 20% perforation generally produced the lowest energy consumption, while 80% perforation consistently led to higher values. Interestingly, for some configurations, 50% perforation combined with a 100–150 mm screen yielded comparable or slightly lower values than 20% perforation, likely due to improved daylight penetration. The influence of screen thickness is summarised in Figure 9c, where increasing thickness reduced energy consumption across all perforation ratios, with 150 mm performing marginally better than 100 mm and significantly better than 50 mm.

5.3. Analysis of Energy Consumption of Various Screen Configurations

Cavity depth emerged as a key factor influencing energy consumption. Across all orientations, increasing the cavity from 0.5 m to 1.0 m significantly reduced cooling demand, while increases beyond 1.0 m yielded smaller gains. Perforation ratio was the next most influential parameter; lower perforation ratios (particularly 20%) led to better shading performance and lower cooling energy. Screen thickness had a secondary but stabilising effect, with a thicker Jaali providing improved performance due to increased shading and thermal mass.

5.4. Peak and Optimal Energy Configurations

As per Figures 7–9, the configuration producing the highest energy consumption in all orientations was achieved with the combination of 0.5 m cavity depth, 80% perforation ratio, and 50 mm thickness. Peak and optimal energy configurations are noted in the south (Table 2), west (Table 3), and east (Table 4) orientations to find the difference in their energy consumption. The lowest energy consumption (optimal case) was achieved with 1.5 m cavity depth, 20% perforation ratio, and 100 mm thickness for the screen on the south façade (Figure 10). The west façade performed best with a 1.0 m cavity, 20% perforation ratio, and 150 mm thickness (Figure 11). The east façade performed best with a 1.5 m cavity, 50% perforation ratio, and 150 mm thickness (Figure 12).

Table 2. Parameters of peak and optimal configuration in the south.

Parameters	Peak Case	Optimal Case
Thickness of Jaali (mm)	50 mm	100 mm
Perforation Ratio (%)	80%	20%
Cavity Depth (m)	0.5 m	1.5 m

Table 3. Parameters of peak and optimal configuration in the west.

Parameters	Peak Case	Optimal Case
Thickness of Jaali (mm)	50 mm	150 mm
Perforation Ratio (%)	80%	20%
Cavity Depth (m)	0.5 m	1.0 m

Table 4. Parameters of peak and optimal configuration in the east.

Parameters	Peak Case	Optimal Case
Thickness of Jaali (mm)	50 mm	150 mm
Perforation Ratio (%)	80%	50%
Cavity Depth (m)	0.5 m	1.5 m

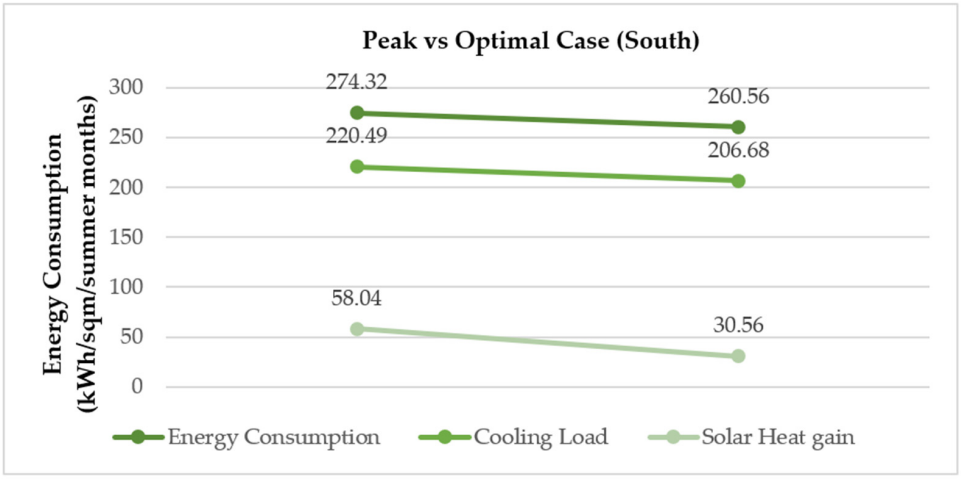


Figure 10. Energy consumption of peak and optimal configuration in the south.

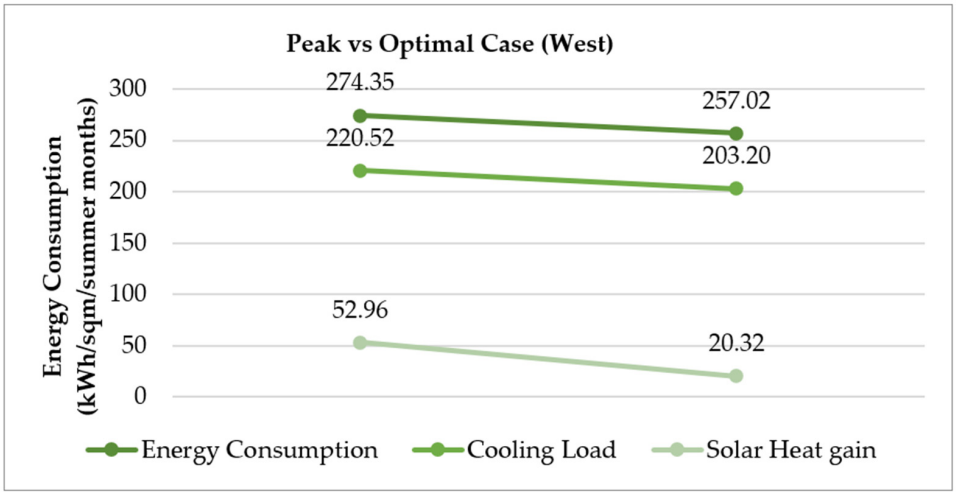


Figure 11. Energy consumption of peak and optimal configuration in the west.

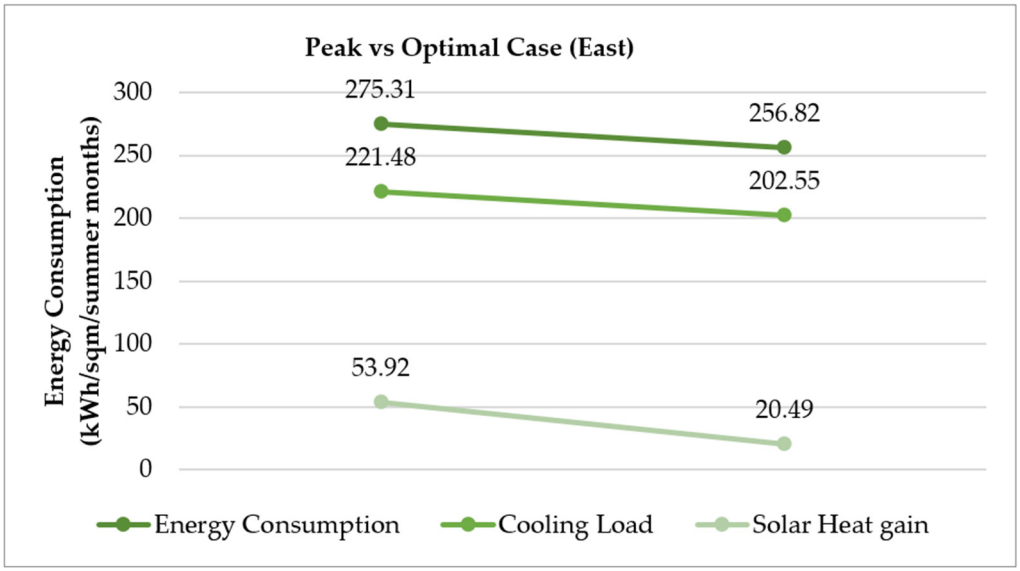


Figure 12. Energy consumption of peak and optimal configuration in the east.

5.5. Overall Energy Saving

As shown in Figure 13, the implementation of Jaali screens significantly reduced energy consumption across all orientations compared with the base case. The south and west façades achieved up to 7.97% reduction, while the east façade achieved the highest reduction of 8.71%. Although the south façade remained the highest consumer overall, Jaali integration narrowed the difference between façades.

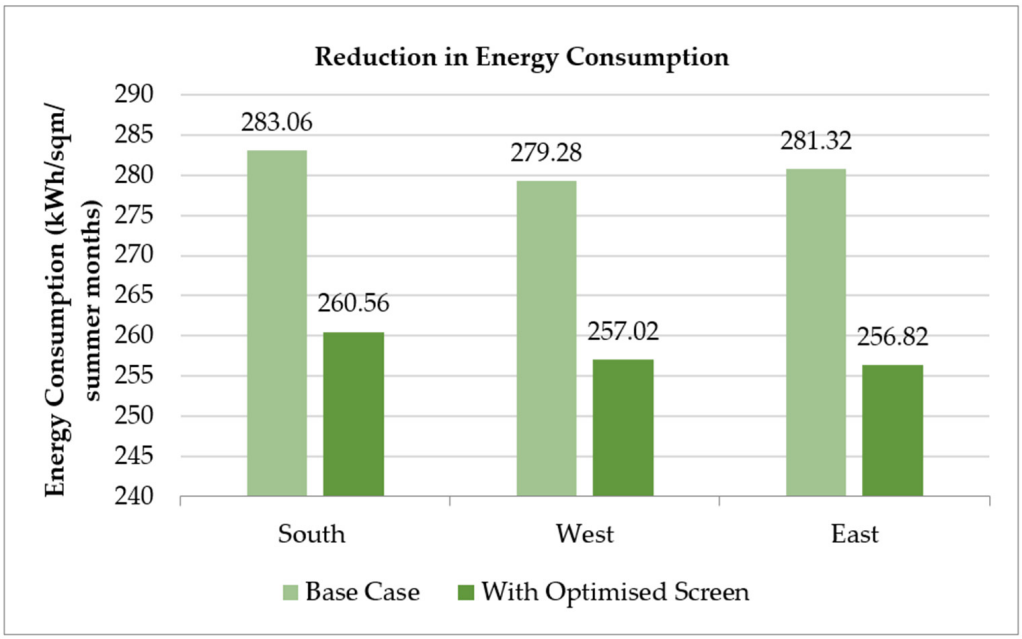


Figure 13. Energy consumption of base case with optimised Jaali across all three orientations.

The east façade receives intense low-angle morning radiation in the early morning hours. Horizontal shading elements are less effective against low solar altitude, whereas perforated Jaali systems reduce direct sunlight on the glazing more efficiently. This explains the higher cooling load reduction observed in the east orientation [44].

5.6. Implication for Predictive Modelling

The complete dataset of 84 simulations (81 Jaali configurations plus three base cases) provides a structured input–output mapping between façade parameters and cooling energy consumption. This dataset forms a robust calibration basis for surrogate or data-driven predictive models, enabling rapid exploration of shading strategies and their influence on building cooling demand at the urban scale.

5.7. Implication for Design

Based on the results, Table 5 summarises the optimal Jaali configurations for each orientation. For the south façade, a 100 mm thick Jaali with 20% perforation and a 1.5 m cavity provided the best performance. For the west façade, a 150 mm thick Jaali with 20% perforation and 1.0 m cavity depth was most effective. For the east façade, a 150 mm thick Jaali with 50% perforation and a 1.5 m cavity achieved the lowest energy use. These configurations are recommended for modern office buildings in Jaipur's hot semi-arid climate to achieve improved thermal performance and reduced cooling energy demand.

Table 5. Optimal configuration across three orientations.

Parameters	South	West	East
Thickness of Jaali (mm)	100 mm	150 mm	150 mm
Perforation Ratio (%)	20%	20%	50%
Cavity Depth (m)	1.5 m	1.0 m	1.5 m

5.8. Economic Considerations

While the energy savings are observed in a range of 8–9% just by installing Jaali on the single façade of the building, adding optimised Jaali on other facades together can have a combined effect on reducing energy consumption during the summer months. Additionally, external shading can substantially reduce peak energy demand, which may influence HVAC sizing and capital cost [54,55].

The commercial electricity tariff in Rajasthan is approximately ₹8–9 per kWh as per the Rajasthan Electricity Regulatory Commission [56]. Based on the total conditioned floor area of 1800 m^2, the energy savings are 22.5 kWh/m^2, 22.26 kWh/m^2 and 24.5 kWh/m^2 in the south, west and east directions, respectively. The operational savings in the summer months will range from ₹3,20,544/- to ₹3,94,900/-.

The approximate cost of concrete Jaali in the region is ₹1500 to 2500 per m^2. The total area of the east and west façades is 360 m^2 each, and the south façade is 540 m^2. Therefore, the total cost of the Jaali on each façade can range from ₹5,40,000/- to ₹13,50,000/-. Hence, the simple payback period will range from 1.7 years to 3.5 years.

6. Discussion

The base case confirmed a clear orientation hierarchy in Jaipur's semi-arid climate, with the south façade exhibiting the highest cooling energy use, followed by the east and west. This pattern reflects greater solar exposure to the south during the summer months and extended morning and afternoon gains on the east and west façades. Introducing a Jaali screen reduced cooling energy in all orientations, aligning with previous studies that demonstrated how external perforated shading systems significantly reduce window-transmitted solar radiation and, consequently, building cooling demand [28,30,31].

Energy savings were greatest on the south façade, where baseline solar gain was highest. This result corresponds with the findings from Kharga Oasis in Egypt, where optimised perforated window screens achieved up to 30% energy savings on west- and south-facing façades, about 26% on the east due to lower direct solar incidence [28] and

7% on north-facing façades. In that desert context, screens with 80–90% perforation and a depth-to-opening ratio of approximately 1:1 performed best, demonstrating that deeper geometries can offset higher porosity. By contrast, in Jaipur's composite climate, lower perforation proved more effective, highlighting the necessity of local adaptation rather than direct transfer of configurations across regions.

The results also indicate that increasing the cavity depth from 0.5 m to 1.0 m significantly reduced cooling energy demand across all orientations, while an additional increase to 1.5 m provided only marginal benefits. This behaviour aligns with previous double-skin façade research in hot dry regions, which identified an optimal 0.9 m cavity depth delivering up to 31% annual cooling energy reduction relative to a single-skin façade and additional savings of 4% on south-facing façades compared to north-facing ones [35]. The performance improvement from cavity depth is likely due to the decrease in sol-air temperature achieved through convective heat dissipation within the air gap [31,44,51].

6.1. Role of Convective Heat Transfer Within the Jaali Cavity

The improvement in energy performance with increasing cavity depth can be attributed to convective heat transfer within the air gap between the Jaali screen and the glazing surface. Solar radiation absorbed by the external screen heats the air in the cavity, generating buoyancy-driven airflow through the stack effect. As the warmer air rises, cooler air enters through the screen pores, accelerating due to the venturi effect and removing heat from the cavity. This process reduces the air temperature adjacent to the glazing surface and lowers the sol-air temperature acting on the building envelope [31,44].

The reduction in cooling energy demand when increasing the cavity depth from 0.5 m to 1.0 m, followed by diminishing improvements at 1.5 m, is consistent with previous studies on ventilated double-skin façades, which show that wider cavities initially enhance heat dissipation through increased airflow circulation; however, beyond an optimal depth, airflow stabilises, and additional increases provide limited thermal benefit [31,51]. The smaller gains beyond 1.0 m suggest that convective exchange approaches a near-steady condition, where further increases in cavity volume do not significantly improve heat removal efficiency.

The cavity between Jaali and glazing in hot semi-arid climates such as Jaipur functions as a thermal buffer zone that reduces direct solar heat gain while simultaneously enabling passive heat removal through airflow, reinforcing the findings from earlier passive façade research in comparable climatic contexts [44]. However, airflow behaviour within the cavity was not modelled in this study, as the simulations relied on energy modelling rather than computational fluid dynamics (CFD) analysis.

6.2. Role of Perforation Ratio

Perforation ratio proved to be the most influential design parameter. Across all orientations, a 20% perforation consistently resulted in the lowest energy consumption, confirming that reduced openness limits direct solar penetration while maintaining sufficient diffuse daylight. These findings are comparable to the Egyptian desert study [28], though differences emerge under varying climatic contexts. For instance, in Doha's hot arid climate, screens with 30% perforation achieved up to 45% energy savings, whereas in Lahore's hot humid climate, 50% perforation was found to perform better because the increased airflow offset higher humidity [34]. Such variation highlights that optimal porosity depends on both solar intensity and ambient humidity conditions.

6.3. Role of Jaali Screen Thickness

Screen thickness showed a smaller influence compared to perforation ratio or cavity depth. Increasing the thickness from 50 mm to 100 mm or 150 mm resulted in modest but

consistent reductions in energy consumption. Prior studies optimising Jaali geometry for daylighting and thermal comfort found that a solid-to-void ratio of 70:30 and a depth of 100 mm provided the best balance between shading and illumination in India's composite climates [10]. Similarly, thermal mass studies revealed that thicker façades enhance short-term heat damping. Aluminium panels, due to their higher reflectivity and lower thermal absorption, outperformed galvanised steel in hot climates, while broader air cavities between 0.05 m and 0.30 m further reduced heat transfer [32]. In hot dry cities such as Seville, a 25% perforation combined with glossy white aluminium yielded the most favourable energy performance [32].

The optimised Jaali configurations in this study achieved 8–9% cooling energy reduction relative to base cases. Although this figure is smaller than some boundary studies, the relative patterns are consistent. In the Egyptian desert case, external perforated screens reduced energy demand by 30% [28]. In Saudi Arabia, traditional Mashrabiya elements lowered operating temperature by 14%, reduced peak solar gains by 78%, decreased monthly cooling load by 6%, and improved daylight efficiency by 36% [33]. Similarly, a study on contemporary office façades in hot climates showed that integrating Mashrabiya as a double-skin façade could cut solar heat gain by up to 78% compared to unshaded glass façades [30].

At the technological extreme, the Al Bahr Towers in Abu Dhabi demonstrated the potential of dynamic Mashrabiyas, achieving a 50% reduction in solar gains, a 20% lower peak cooling demand, and 40% lower annual carbon emissions and saving approximately 1750 tons of CO_2 per year while maintaining indoor illuminance between 250 and 2000 lux [12,38,39]. These precedents confirm that both fixed and adaptive perforated systems significantly improve energy efficiency and comfort, with the degree of benefit depending on system type, climate, and building envelope.

Other research revealed that the use of traditional Mashrabiya greatly enhances both thermal comfort and energy efficiency. Computational models demonstrated that the integration of Mashrabiya can result in a 14% decrease in operating temperature and a 77.8% decrease in peak solar gain, therefore improving the cooling effectiveness of buildings, as shown in Figure 14. Moreover, it led to a 5.7% decrease in the amount of cooling load needed on a monthly basis and a 35.5% enhancement in the efficiency of natural light, thereby showcasing its capacity to decrease energy usage in residential structures as shown in Figure 15 [33].

These results from case studies show that the Jaali façade consistently reduces daily cooling loads throughout the month, with the most pronounced reductions occurring during periods of high solar radiation. This indicates that the perforated shading system effectively limits direct solar heat gains while still allowing air movement through the façade cavity. The daily variation analysis provides further insight beyond annual energy totals, demonstrating that the Jaali façade not only reduces overall energy demand but also moderates peak cooling loads during the hottest days of the year.

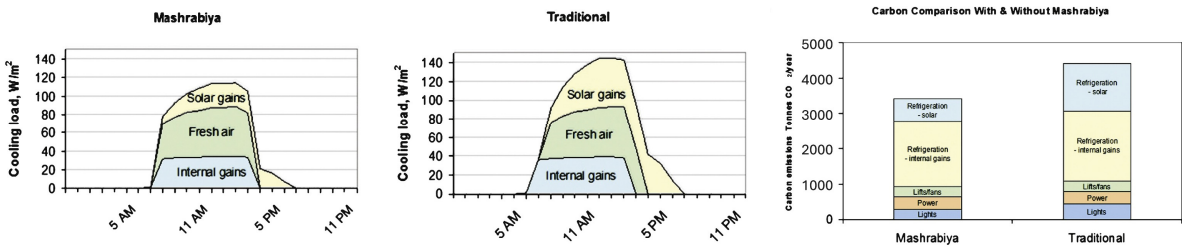


Figure 14. Solar heat gains on facade with and without Mashrabiya of Al Bahr Center [12].

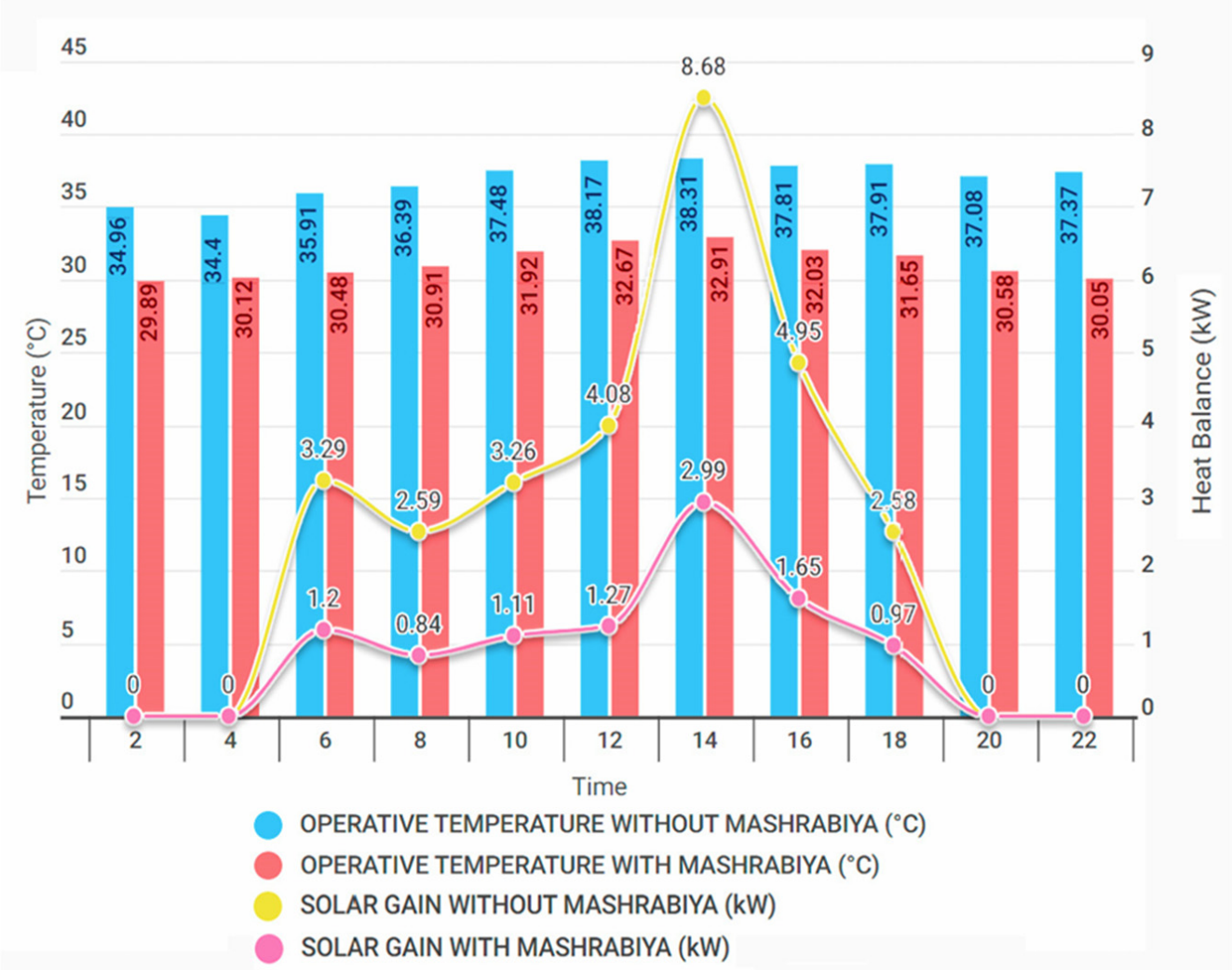


Figure 15. Difference in temperatures due to solar heat gain with and without Mashrabiyas [33].

The findings suggest specific orientation-based guidelines for semi-arid Indian cities such as Jaipur. South façades benefit from deeper cavities (1.0–1.5 m) combined with low perforation (20%), optimising shading against midday solar exposure. West façades, dominated by low-angle afternoon sun, achieve maximum benefit with a 1.0 m cavity depth and similar low perforation. East façades, influenced by shorter morning exposure, can balance shading and daylight with 50% perforation and a 1.5 m cavity depth, especially when paired with thicker screens (150 mm). Screen thickness between 100 and 150 mm remains adequate across all orientations, offering durability and sufficient thermal resistance without unnecessary material use. These results support the broader conclusion from prior research in Egypt [28], Saudi Arabia [33] and India [10] that orientation-sensitive passive design offers measurable and scalable energy advantages.

The 84 simulation configurations provide a robust dataset for predictive modelling. Machine learning frameworks have recently demonstrated enhanced performance when trained on similar parametric datasets. For example, Olu-Ajayi et al. achieved over 20% lower mean absolute error than conventional regressions by using deep neural networks to predict building energy demand from simulation outputs [36]. Similarly, Brambilla et al. found that genetic algorithms and particle swarm optimisation could identify optimal façade configurations 30% more efficiently than manual approaches [37]. Treating the Jaali dataset as a surrogate model base enables rapid prediction of façade performance across

large urban contexts, supporting early-stage design decisions and urban energy mapping without the need for repetitive full-physics simulation [57].

This study isolates summer cooling performance and excludes daylight control and winter heating effects. Some studies report higher savings from integrated lighting control and adaptive shading [12,39]. Future research should, therefore, couple cooling energy with daylight autonomy and glare probability, extend analysis to the shoulder and winter seasons, and validate predictions against monitored field data. Additionally, comparative cost, maintenance, and constructability studies could determine the viability of Jaali systems relative to low-emissivity glazing or dynamic electrochromic façades. Extending this framework to other Indian climates as well as comparable hot arid contexts would help define the climatic conditions under which Jaali systems remain effective and assess their scalability for sustainable urban design.

6.4. Maintenance

Although Jaipur experiences periodic dust events due to its proximity to the Thar Desert, the maintenance required for perforated Jaali systems remains relatively manageable compared with mechanically operated façade technologies [58]. These traditional Jaali elements have historically been constructed in stone or concrete with smooth or carved surfaces, which allows accumulated dust to be removed through manual washing or low-pressure water cleaning without specialised equipment. Studies on façade maintenance in hot arid climates indicate that static external shading devices typically require only periodic surface cleaning to restore performance, in contrast to dynamic systems that involve mechanical components and control mechanisms requiring technical servicing [59].

6.5. Future Research

The findings of this study are based on the climatic conditions of Jaipur, characterised by high solar radiation and large diurnal temperature variation typical of hot semi-arid climates. The effectiveness of perforated shading systems such as Jaali façades is, therefore, closely linked to solar intensity and façade exposure conditions. In climates with higher humidity levels or lower solar radiation, such as tropical or temperate regions, the thermal benefits may differ due to variations in solar gain and ventilation potential. Future research should extend the simulation framework to multiple climatic zones in order to evaluate the broader applicability of Jaali façade systems under diverse environmental conditions.

The Jaali in this study is made of concrete. Therefore, the impact of modern materials such as wood, aluminium or stainless steel can be studied. Future studies can include a wider range of parameters to get more optimal and precise results using advanced multi-objective optimisation. Future studies can also carry out both lighting and cooling energy simulations, which are beyond the scope of the current research. The broader assessment of manufacturing of Jaali should be studies on the basis on embodied carbon and circular economy.

7. Conclusions

This research addressed the pressing challenge of cooling energy demand in hot semi-arid regions such as Rajasthan, where prolonged summer temperatures place significant stress on building energy systems. Through detailed simulation-based analysis, this study examined the influence of Jaali screens used as double-skin façades on the energy performance of an office building in Jaipur, India. By systematically varying orientation, cavity depth, perforation ratio, and screen thickness, this study identified configurations that optimise shading performance and cooling energy reduction. This study establishes new performance evidence for Jaali-based façade systems in the hot dry Indian urban context,

which differs from other hot arid desert climates in terms of urban form, cultural practices, local climate parameters, urban heat island intensity, and economic constraints.

The findings confirm that Jaali integration can meaningfully reduce cooling loads, particularly on façades with high solar exposure. The most effective configurations include a cavity depth of 1.0–1.5 m and a low perforation ratio of around 20%, with screen thickness between 100 and 150 mm. South façades benefited most from deeper cavities, while east façades achieved balanced results with moderate perforation (50%) when daylighting needs were considered. These results align with studies conducted in Kharga Oasis (Egypt), Doha (Qatar), and Seville (Spain), which similarly found that screen geometry and climatic context jointly determine façade energy performance.

By comparing fixed Jaali systems with other passive and dynamic shading precedents, this study situates its findings within a broader body of regional and international research. Although the observed energy savings of 8.0–8.7% are smaller than those reported for adaptive or kinetic systems, such as the Al Bahr Towers in Abu Dhabi, they represent realistic, cost-effective outcomes for fixed passive façades in a composite Indian context. This study thus demonstrates how traditional architectural elements, when optimised using modern simulation tools, can substantially improve thermal performance in contemporary office buildings.

Beyond design guidance, this research contributes a structured dataset of 84 simulation cases that can serve as a benchmark for predictive modelling and data-driven optimisation of façade performance. These parametric results can be used to train machine learning models for rapid energy prediction, scenario testing, and urban-scale applications where computational efficiency is essential. Overall, this study bridges traditional passive cooling wisdom with contemporary simulation and computational techniques. It provides clear, orientation-specific design recommendations for the effective application of Jaali screens in modern façades and highlights their potential role in advancing energy-efficient, climate-responsive architecture across hot semi-arid regions such as Jaipur.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Ac/h	Air Changes per Hour
AC	Air Conditioning
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
CO_2	Carbon Dioxide
DDPMs	Daylight Dynamic Performance Metrics
DGP	Daylight Glare Probability
DSF	Double-Skin Façade
ECBC	Energy Conservation Building Code
EPW	EnergyPlus Weather
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
ISHRAE	Indian Society of Heating, Refrigerating, and Air Conditioning Engineers
kWh/m^2	Kilowatt-hours per Square Meter
PMV	Predicted Mean Vote
SDG	Sustainable Development Goals
RCC	Reinforced Cement Concrete
TMY	Typical Meteorological Year
UHI	Urban Heat Island
UAE	United Arab Emirates
U-value	Thermal Transmittance
W/m^2 K	Watts per Square Meter per Kelvin
Wh	Watt-hour

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