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Bioclimatic Design Strategies for Optimizing Natural Ventilation in Low-Cost Housing: Simulation of Window Placement, Size, and Building Orientation

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ABSTRACT

This paper explores the integration of bioclimatic architecture to enhance indoor air quality through the use of natural ventilation. Natural ventilation involves the passive exchange of air within a building, facilitated by openings and building elements. The motivation behind this study stems from the growing concern that architectural developments for low-cost housing in Indonesia often neglect the importance of adequate natural ventilation, prioritizing market-driven designs over the optimization of air circulation. This issue has gained further significance in the wake of the COVID-19 pandemic, which has highlighted the need for healthier living environments. The research employs a descriptive quantitative approach, utilizing case study analysis and simulation techniques. The findings show that a building's orientation, shape, and window designs can be optimized to improve natural ventilation. It is anticipated that flats designed with bioclimatic principles will respond effectively to local climatic conditions and reduce reliance on mechanical cooling, thereby enhancing occupant well-being.

Keywords: bioclimatic, low-cost, natural, passive, ventilation

1. Introduction

Indonesia, with its tropical climate, experiences high temperatures and humidity levels, necessitating the frequent use of air conditioning systems to regulate indoor comfort. This reliance on artificial cooling results in substantial energy consumption. A report by the WWF Institute [1] indicates that air conditioning (AC) constitutes a major contributor to residential energy usage. Consequently, the design of buildings that can respond efficiently to local climate conditions is critical for ensuring thermal comfort while minimizing energy consumption. For low-income communities, particularly in low-cost apartments in Indonesia, it is essential to reduce energy expenses without compromising residents' well-being. Moreover, effective natural ventilation is vital in maintaining indoor air quality, especially following the COVID-19 pandemic, which heightened concerns about air circulation and disease prevention. Insufficient ventilation can also lead to the development of sick building syndrome, impacting the health and comfort of inhabitants. Many apartment buildings in Indonesia, unfortunately, overlook the importance of optimizing air circulation.

One potential solution is bioclimatic architecture, an approach within the field of ecological architecture. This design philosophy advocates for buildings that adapt to local climatic conditions through passive strategies.

These strategies involve methods to minimize reliance on non-renewable energy while enhancing occupants' health and comfort. Bioclimatic architecture considers various factors, including the macro- and microclimate, to create designs that promote energy efficiency and improve thermal conditions [2]. Ken Yeang (1994) [3] emphasized the importance of understanding the interrelationship between climate and human activities, particularly its influence on health and daily life. The design of buildings using this approach incorporates elements such as orientation, shading, and ventilation, all of which directly respond to the surrounding climate.

Passive design principles are a core aspect of bioclimatic architecture, utilizing natural resources like sunlight and wind for lighting and ventilation, reducing the need for electrical energy. To effectively implement passive systems, it is essential to understand local climate patterns, identify optimal comfort zones, and design building elements such as windows and openings that maximize natural airflow. These design principles contribute to creating a built environment that is both sustainable and responsive to local conditions [4]. In the context of multi-story buildings in tropical regions, considerations include the arrangement of building mass, the orientation to minimize heat exposure, and the strategic use of openings to enhance natural ventilation and thermal comfort [4]. This study aims to explore the impact of building orientation, the positioning of windows, and the size of openings on optimizing natural ventilation in low-cost housing.

Given the importance of climate-responsive design and the potential of passive strategies to improve both energy efficiency and occupant well-being, numerous studies have investigated the impact of building orientation and opening designs on optimizing natural ventilation in tropical climates, particularly in Indonesia. Numerous studies have explored the role of building orientation and opening designs in enhancing the effectiveness of natural ventilation in tropical climates, particularly in Indonesia.

In a study examining natural air conditioning in industrial flats [5], it was found that the orientation of buildings significantly impacts the efficiency of natural ventilation. The research recommended positioning buildings with an east-west alignment to minimize solar heat gain on the longest sides, while openings should be strategically placed to align with the prevailing wind direction. Such configurations help improve airflow and reduce the likelihood of humidity accumulation. To optimize wind intake, facade modifications, such as the incorporation of fins, were proposed. Additionally, the study suggested that window dimensions and placements adhere to ACH (air change per hour) standards, ensuring effective ventilation. With these adjustments, the study observed indoor wind speeds of 0.5 m/s and an average room temperature of 25°C, in line with Indonesia's comfort standards. A separate study on the impact of openings on thermal comfort in the residential units of Aparna Flats in Surabaya [6] emphasized that building orientation should still follow the east-west direction to maximize exposure to wind, while openings must be carefully positioned to avoid creating thermal discomfort. The study found that small window sizes were a key issue, obstructing efficient airflow, and recommended larger openings for better ventilation. In this case, the room temperature reached 29°C, which is slightly above the comfort range, suggesting that additional passive shading strategies, such as the use of canopies, were necessary to mitigate excess solar gain.

Another investigation into the effects of building orientation and wind speed on the design of facades for flat buildings [7] underlined the importance of adapting facades to local wind conditions, especially in coastal areas where strong winds carry salt. This study recommended adding secondary layers, or "skins," to the building facades to reduce wind speed and prevent discomfort. Incorporating plants into the facade was also suggested to absorb salt and improve indoor comfort. After adjusting the building's facade and adding passive shading, the study noted a reduction in room temperature from 31°C to 27°C, which met the thermal comfort standards. Similarly, a study on natural air conditioning strategies for the Jarrdin Flats [8] reinforced the importance of east-west orientation for optimizing air circulation and minimizing solar heat gain. However, it also highlighted the need for proper window sizing and internal design, especially the corridors, as narrow corridors hindered cross-ventilation. The authors suggested increasing window sizes and improving the corridor design. Additionally, extending the canopy length was recommended to improve shading and prevent rainwater infiltration, which would ultimately improve the building's overall thermal comfort.

In another study on natural ventilation in flats [9], similar findings were reported, emphasizing that a correct building orientation, combined with larger, well-placed windows and the use of double-loaded corridors for enhanced cross-ventilation, would significantly improve indoor air quality. Additionally, passive shading strategies, such as extending canopies, were identified as crucial in reducing solar exposure and increasing occupant comfort. Further research into the optimization of building orientation and natural ventilation has revealed additional strategies. A study by Soraya et al. [10] explored the role of natural ventilation in reducing energy consumption in low-cost housing, stressing the importance of designing buildings that respond efficiently to the local climate. Wibowo and Hadi [11] discussed how building orientation, when paired with passive ventilation strategies, can enhance energy efficiency in tropical housing, offering solutions for both cooling and ventilation needs. Hidayat [12] evaluated the effectiveness of various natural ventilation strategies for multi-story buildings in Jakarta, providing insights into the importance of proper wind direction and building orientation in enhancing airflow.

Rahayu and Kusuma [13] focused on the role of cross-ventilation in improving thermal comfort in low-cost apartments, while Adi and Shinta [14] explored efficient ventilation system designs for tropical buildings. Santosa [15] discussed the management of airflow and building orientation in high-rise residential structures, emphasizing the need for design strategies that facilitate natural ventilation. Finally, Pratama [16] assessed the effectiveness of wind flow in multi-story residential buildings, recommending the use of proper facade designs and building mass configurations to optimize ventilation.

2. Method

The design approach for the low-cost flats with a bioclimatic concept follows a descriptive quantitative methodology, using both programmatic and pragmatic methods to address the problem and analyze the current conditions. The process begins by identifying the existing conditions according to established theory and design standards. This allows for a comprehensive understanding of the site, climate factors, and the functional requirements of the building. The first phase involves applying bioclimatic design principles, which incorporate a synthesis of the theoretical framework and practical design parameters. The design is then analyzed through a synthesis phase to ensure it responds appropriately to the climate, energy efficiency, and occupant comfort.

In the next phase, the design is evaluated using evaluative methods, where CFD (Computational Fluid Dynamics) software is employed to simulate airflow and temperature distribution within the building. This allows for the testing of design elements, such as building orientation, window placements, and opening sizes, to ensure optimal natural ventilation and thermal comfort. The simulation results are then compared against comfort standards, including the Air Change per Hour (ACH) criteria, to verify the effectiveness of the proposed design in solving the identified issues and meeting the required comfort levels. This method not only evaluates the technical success of the design but also provides data-driven insights for further design optimization.

3. Result and Discussion

In this study, the site selected is located on Kampung Bandan street, RT.5/RW.4, Ancol, Pademangan district, North Jakarta, Indonesia. The site currently consists of slum housing, and the project aims to build a flat for the relocation of residents from the East Pademangan sub-district. The land was chosen due to its residential zoning, making it an appropriate location for the new development. This visual information in Figure 1 provides a foundational understanding of the site’s location and its surroundings, which is essential for assessing the environmental and urban dynamics of the area. By referencing the satellite view and land use map, the study can better inform the design of the flat project, ensuring that it not only aligns with the residential zoning but also responds effectively to the local climate and urban conditions of North Jakarta.

(a) (b)

Figure 1. (a) Satellite view of the site location in Pademangan, (b) Map of land use in Jakarta

Site and Building Orientation

The building's orientation is a key factor in designing a climate-responsive structure, aimed at enhancing thermal comfort and indoor air quality. The orientation is divided into two main categories: orientation to the sun path and orientation to wind flow. For the sun path orientation, the building’s longer side is aligned along the north-south axis, while the shorter side runs east-west. This configuration ensures sufficient solar exposure on the longer side, while avoiding direct sunlight from the east and west, allowing optimal placement of openings for natural lighting and ventilation without excessive heat gain. In terms of wind flow orientation, the building should follow the predominant wind direction to facilitate effective air circulation throughout. According to data from the Central Bureau of Statistics Jakarta (2015), the most common wind direction in North Jakarta is from the southwest to the northeast and vice versa. This wind pattern is considered when determining the building’s orientation to ensure smooth airflow, helping to maintain thermal comfort and indoor air quality.

Table 1. Annual wind movement data

Month	Wind Direction	Wind Speed (m/s)
1	202,5 - 247,5 (Southwest)	2,9
2	202,5 - 247,5 (Southwest)	2,6
3	202,5 - 247,5 (Southwest)	3,2
4	202,5 - 247,5 (Southwest)	2,6
5	22,5 - 67,5 (Northeast)	2,5
6	22,5 - 67,5 (Northeast)	2,6
7	22,5 - 67,5 (Northeast)	2,8
8	22,5 - 67,5 (Northeast)	2,6
9	22,5 - 67,5 (Northeast)	2,6
10	22,5 - 67,5 (Northeast)	2,6
11	202,5 - 247,5 (Southwest)	2,5
12	202,5 - 247,5 (Southwest)	2,3
	Average Speed	**2,65**

Wind Flow Simulation and Analysis

Based on the wind movement data, CFD simulations were conducted to explore various building orientation alternatives. The results of the simulation are presented in Figure 2, showing the wind circulation within the building. The analysis indicates that the building mass oriented along the southwest-northeast axis responds well to prevailing winds, while still maintaining an east-west orientation to manage sunlight exposure. This orientation allows all residential units to benefit from sufficient natural ventilation, with wind speeds reaching the desired comfort standards.

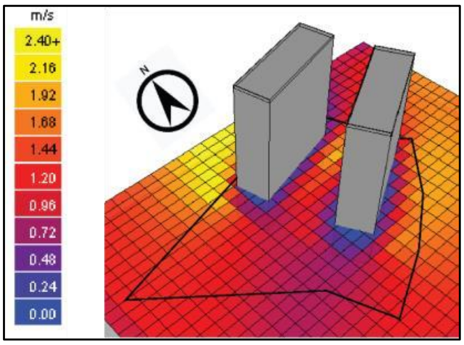


Figure 2. Simulation of wind circulation

Optimal Building Orientation

The best orientation derived from the analysis is a multi-mass building with a rectangular shape (I-shape), oriented southwest-northeast. This configuration enables the longest side of the building to receive direct airflow while minimizing exposure to solar heat on the shorter sides. This building layout effectively utilizes natural ventilation and thermal comfort strategies (Figure 3).

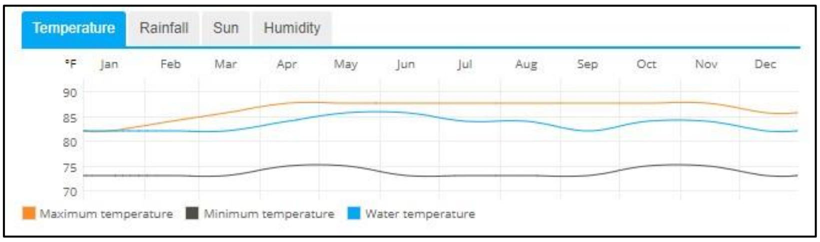


Figure 3. Pademangan annual temperature graph

Thermal Comfort and Wind Speed

The climate in the Pademangan area features an average maximum temperature of 30°C (87°F) and a minimum of 23°C (75°F). Given these temperatures, natural ventilation plays a key role in maintaining thermal comfort. The wind entering the building is designed to achieve a comfortable airflow speed of 0.5 m/s, which aligns with Indonesia's national standards for indoor comfort.

The positioning of windows and doors is crucial in ensuring that both sunlight and airflow can be effectively managed. In addition to window placement, the size of the openings affects the Air Change per Hour (ACH), which ensures that indoor air is neither too humid nor too dry. The design accommodates the relatively high humidity in the Pademangan area, which reaches up to 79%, by allowing sufficient airflow and preventing mold and other issues related to dampness.

Window Design and Airflow Calculations

The necessary window opening area for residential (Table 2) comfort was determined using the ACH formula:

$$N = 3600 \times Q/V \tag{1}$$

Where,

- N = ACH value
- Q = Airflow into space (m^3/s)
- V = Volume of space (m^3)

For specific window designs, the airflow calculation involves:

$$\mathbf{Q} = 0{,}025 \times \mathbf{A} \times \mathbf{v} \qquad (2)$$

Where,

- A = Area of the opening (m²)
- v = Wind speed at the opening (m/s)

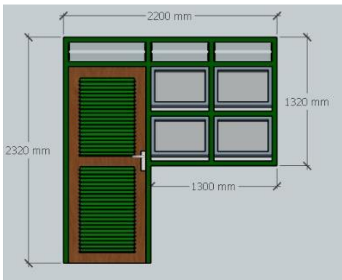
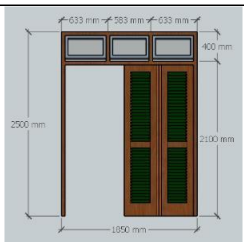
Table 2. Window types and effectiveness

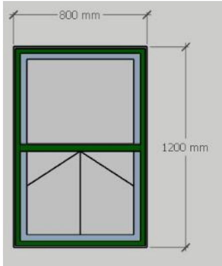
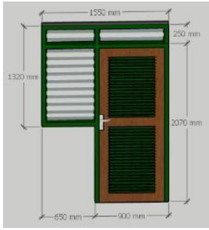
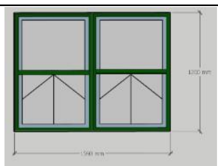
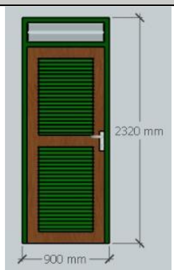
Type	Effectiveness (%)
Single Hung	90
Double Hung	45
Awning	75
Casement	90
Jalousie	75
Horizontal Sliding	75

From the analysis, the design of each room's openings is adjusted to meet the ACH standards while ensuring that the wind speed inside the apartment remains within the comfort range of 0.25 – 0.5 m/s (Table 3).

Table 3. Window Types and Required Opening Sizes

Name of Room	Room Space (m2)	Room Volume (m3)	Constanta	Wind Speed (m/s)	ACH Minimum	Large of Opening Minimum (m2)
Master bedroom	7,5	22,5	0,025	2,65	4	0,37
Bedroom	6	18	0,025	2,65	4	0,3
Living room	14	42	0,025	2,65	5	0,88
Kitchen	7	21	0,025	2,65	15	1,32
Toilet	4	12	0,025	2,65	6	0,3

<table>
<tr><th>Code</th><th>Image</th><th>Description</th></tr>
<tr><td>PJ1</td><td>
</td><td>Opening for living room Type of opening:
• Awning: effectiveness 75% = 1,12 x 75% = 0,84 m²
• Jalousie: effectiveness 75% = 0,4 x 75% = 0,3 m²
• Cumulative opening effectiveness = 0,84 + 0,3 = 1,14 m² This inlet opening is for the family room and is appropriate, where according to calculations, the minimum opening area = 0,88 m²</td></tr>
<tr><td>PJ2</td><td>
</td><td>Opening for children's bedroom, Outlet opening type:
• Awnings: 75% effectiveness = 0.58 x 75% = 0.43 m2</td></tr>
</table>

J2		Opening for children's bedroom, Inlet opening type: • Single hung: 90% effectiveness = 0.39 x 90% = 0.35 m^2 Total effective opening area of children's bedroom = 0.43 + 0.35 = 0.78 m^2 This inlet opening is for a child's bedroom and is appropriate, where according to calculations, the minimum opening area = 0.3 m^2
PJ3		Opening for Kitchen Opening type: • Jalousie: 75% effectiveness = 1.79 x 75% = 1.34 m2 This inlet opening is for the kitchen and is appropriate, where according to calculations, the minimum opening area = 1.32 m2
J1		Opening for master bedroom, Inlet opening type: • Single hung: 90% effectiveness = 0.78 x 90% = 0.7 m^2
P1		Opening for master bedroom, Outlet opening type: • Jalousie: 75% effectiveness = 0.16 x 75% = 0.12 m^2 The total effective opening area of the master bedroom = 0.7 + 0.12 = 0.82 m^2 This inlet opening is for a child's bedroom and is appropriate, where according to calculations, the minimum opening area = 0.37 m^2

CFD Simulations and Results

The window and opening designs were simulated using CFD software to assess airflow and temperature conditions in different locations within the building. The results are presented in Figure 5 through Figure 7, showcasing airflow simulations for different rooms.

- Location 1: The average wind speed is 0.45 m/s, which aligns with the comfort standard, and the room temperature is 26°C, which is within the acceptable thermal comfort range of 21-28°C.
- Location 2: Wind speed in the living room is slightly lower at 0.30 m/s, but still within comfort standards. The room temperature is 24°C, comfortably within the desired range.
- Location 3: Wind speed is 0.23 m/s due to wind blockage by other buildings, but the room temperature remains at 26°C, meeting the thermal comfort standards.

These results indicate that the design successfully meets the required comfort standards for both airflow and temperature, demonstrating the effectiveness of the proposed bioclimatic design (Figure 4).

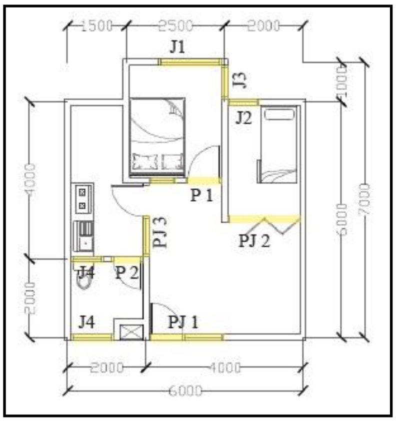


Figure 4. Unit design

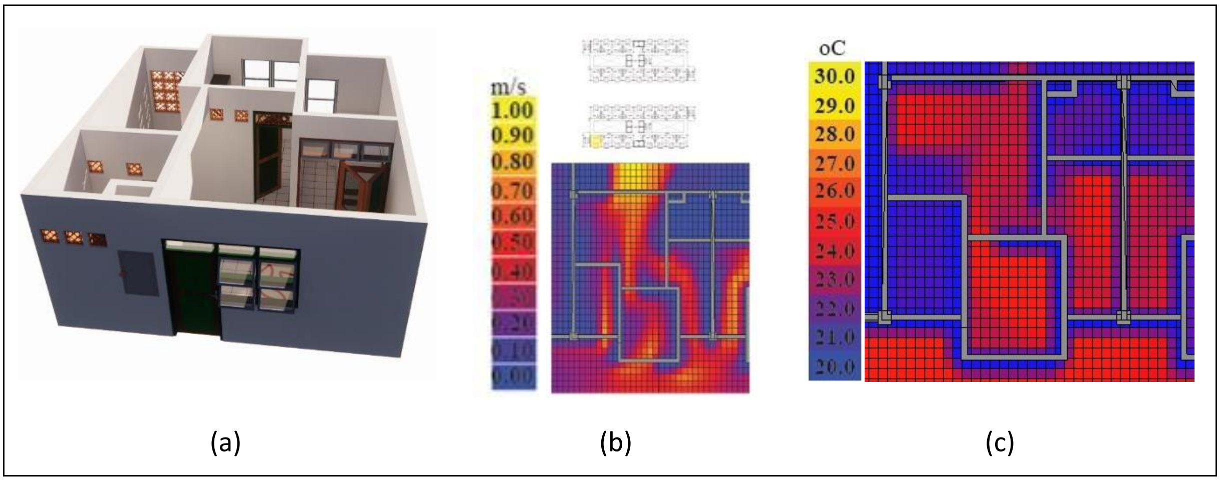


Figure 5. (a) 3D unit design, (b) Air flow simulation in location 1, (c) Temperature simulation in location 1

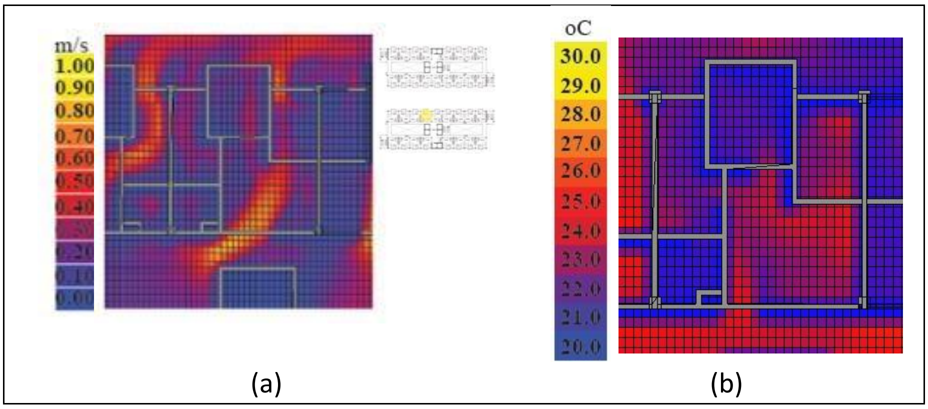


Figure 6. (a) Air flow simulation in location 2, (b) Temperature simulation in location 2

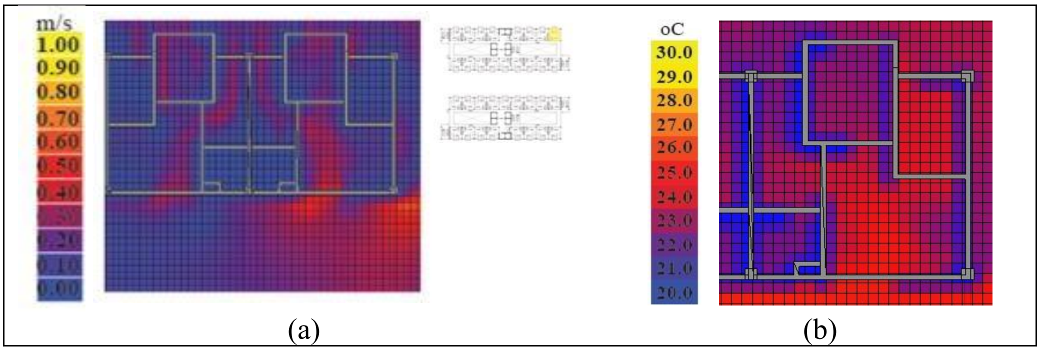


Figure 7. (a) Air flow simulation in location 3, (b) Temperature simulation in location 3

The results from the wind flow simulations, thermal comfort analysis, and CFD modeling demonstrate that the proposed bioclimatic design for the low-cost housing units in Pademangan is highly effective in optimizing natural ventilation and maintaining indoor thermal comfort. The orientation and design choices, particularly the southwest-northeast alignment and the careful positioning and sizing of windows, ensure adequate airflow and temperature regulation, meeting Indonesia's comfort standards. The integration of these passive design strategies, supported by CFD simulations, confirms the design's suitability for addressing both environmental and health concerns, ensuring that residents will experience a comfortable and energy-efficient living space. Further refinement of the design can continue based on these findings to achieve even greater sustainability and occupant well-being.

4. Conclusion

This study emphasizes the importance of bioclimatic architecture in improving the energy efficiency and thermal comfort of low-cost housing in tropical climates, particularly in Indonesia. Bioclimatic architecture integrates climate-responsive strategies, such as building orientation and natural ventilation, to achieve better air quality and reduce reliance on mechanical cooling systems. The findings show that adopting these principles can significantly enhance the indoor environment in terms of air circulation and temperature regulation, aligning with the comfort needs of residents. The results from the simulations and analyses demonstrate that the building's orientation, with a southwest-northeast alignment, allows for effective natural ventilation, ensuring that airflow reaches both sides of the building while minimizing excessive solar exposure. Proper placement and sizing of openings, calculated using the Air Change per Hour (ACH) formula, are critical for maintaining a comfortable indoor environment. These measures reduce indoor wind speed to between 0.25 m/s and 0.5 m/s, which is within the acceptable comfort range, while the room temperature remains within the ideal 24°C to 28°C range. The implementation of these bioclimatic design elements supports the goal of creating low-cost, energy-efficient housing that enhances the quality of life for residents, making it a sustainable solution for urban development.

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6. Conflict of Interest

The authors declare no conflict of interest in the research and publication of this paper.

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