Performance Analysis of Green Wall Ventilation Blocks Toward Sustainable Building Design

Harry wibowo[1], Siti Zulfa Yusni[2], Zhilli Izzadati Khairuni[3], Denny Meisandy Hutauruk[4]

harry_ft@unimed.ac.id[1], sitizulfa@unimed.ac.id[2], zhilli_ft@unimed.ac.id[3], denny_ft@unimed.ac.id[4]

[123]Architecture Study Program, [4]Civil Engineering Study Program, Department of Building Engineering Education, Faculty of Engineering, Universitas Negeri Medan

Abstract. The integration of green wall systems into building envelopes has gained significant attention as a passive design strategy to enhance thermal comfort and promote sustainable architecture. This study presents a performance analysis of environmentally friendly ventilation blocks designed specifically for green wall applications in tropical climates. The ventilation blocks were fabricated using eco-friendly materials, including a mixture of recycled aggregates and natural binders, to reduce the environmental footprint of the building components. Airflow behavior and thermal performance were simulated using computational fluid dynamics (CFD)-based software to assess their effectiveness in enhancing natural ventilation and indoor air quality. Several design variations of the ventilation blocks were tested to examine the influence of geometry and porosity on airflow rate, pressure drop, and air temperature reduction. The results indicate that certain block configurations significantly improve air circulation while contributing to energy savings by reducing the need for mechanical ventilation. This research supports the development of sustainable building components that align with green architecture principles and offers insights for architects and engineers in optimizing passive ventilation strategies through material innovation and simulation-based design

Keywords: green wall, ventilation block, sustainable design, passive ventilation, CFD simulation, eco-friendly.

1 Introduction

Global climate change and the increasing energy consumption of buildings have driven the development of more sustainable architectural design approaches. The building sector accounts for more than 40% of global energy consumption, with a significant portion used for cooling and ventilation systems in tropical regions [1]. Therefore, the integration of passive ventilation systems has become an essential strategy for reducing carbon footprints and improving building energy efficiency.

One emerging approach is the application of green wall systems, which not only serve as aesthetic elements but also contribute to enhancing thermal performance and indoor air

quality. Vertical greenery systems can reduce wall surface temperatures by up to 11°C through mechanisms of evapotranspiration and shading, thereby decreasing the workload of Heating, Ventilation, and Air Conditioning (HVAC) systems [2].

However, the effectiveness of green walls largely depends on their design and the materials used in their modular components. Selecting environmentally friendly building materials can improve thermal performance without significantly increasing construction costs [3]. Furthermore, the use of Computational Fluid Dynamics (CFD)-based simulations provides deeper insights into airflow behavior and temperature distribution both around and within buildings. CFD simulations can identify areas of air stagnation and provide quantitative data that are valuable for optimizing passive ventilation design [4].

Based on this background, the present study focuses on analyzing the performance of eco-friendly ventilation blocks specifically designed for green wall applications in tropical climates. This study integrates material innovation, variations in geometric design, and CFD simulation approaches to evaluate their influence on natural airflow circulation and indoor thermal comfort. The findings are expected to contribute to building design practices that are more adaptive to climate conditions and aligned with the principles of sustainable architecture.

2 Literature Review

Green Wall Systems as Passive Design Strategies

Green wall systems, also known as vertical greenery systems (VGS), have been widely recognized as a passive design approach to enhance building thermal performance and urban microclimate. Their multifaceted benefits include insulation, shading, evapotranspiration, and urban biodiversity enhancement [5]. In hot-humid climates, green walls can act as a thermal buffer, reducing solar heat gain through the building envelope [6]. Moreover, green wall systems can improve air quality by trapping particulate matter and absorbing pollutants. Vegetation in VGS is capable of capturing NO_2 and PM_{10}, supporting healthier indoor and outdoor environments [7]. Despite their benefits, green wall implementations in tropical countries face challenges related to structural weight, maintenance, and material resilience—highlighting the need for more integrated and climate-adaptive designs.

Eco-Friendly Ventilation Blocks and Material Innovation

The materials used for green wall modules and ventilation blocks are crucial for ensuring environmental performance and long-term sustainability. Eco-friendly alternatives—such as geopolymer concrete, fly ash composites, and recycled aggregates—have been proposed to replace traditional Portland cement-based materials. Geopolymer materials emit up to 80% less CO_2 during production compared to ordinary Portland cement [8]. Incorporating pozzolanic materials and agricultural waste (e.g., rice husk ash or palm oil fuel ash) into construction components also improves thermal resistance and durability [9]. These

innovations not only reduce the environmental footprint but also support circular economy principles in construction. Furthermore, ventilation block geometry and porosity significantly affect airflow, heat exchange, and daylight penetration. Shape optimization of passive ventilation components can lead to up to 30% improvement in air change rates under natural conditions [10].

CFD Simulation in Building Performance Analysis

Computational Fluid Dynamics (CFD) has become a reliable tool to simulate and predict airflow patterns, temperature gradients, and pollutant dispersion in building environments. Its integration into architectural design processes allows for more informed decisions in optimizing passive systems. The accuracy of CFD simulations in natural ventilation studies has been confirmed when validated with experimental data [11]. Recent studies also demonstrate the application of CFD in evaluating complex forms and porous materials. For instance, CFD analysis of airflow through customized ventilation panels revealed that even minor geometric changes could lead to substantial differences in pressure drop and indoor comfort levels [12]. The integration of CFD in early-stage design supports the development of prototypes that are both functional and environmentally responsive.

3 Research Methodology

This study adopts an exploratory-quantitative approach focusing on the design and performance analysis of several variations of green ventilation blocks (GVB) for application in green wall systems of buildings located in tropical climates. The primary objective is to evaluate eco-friendly ventilation block designs that can support natural airflow circulation, provide aesthetic quality as façade elements, and accommodate plants with optimal lighting and growing media conditions.

The first stage involved a literature review to identify design principles of passive ventilation systems and green walls within the context of sustainable tropical architecture. The findings from this review formed the basis for developing several alternative GVB designs using parametric design software such as Rhinoceros 3D and Grasshopper. Each model was generated with variations in opening geometry, planting space proportions, and airflow and light orientation. The designs were coded for identification (e.g., GVB-01, GVB-02, and so forth) and modeled at full scale for performance simulation.

Performance simulations of each ventilation block model were carried out using Computational Fluid Dynamics (CFD) software such as Autodesk Vasari. The simulations were conducted under tropical climate scenarios with wind speeds ranging from 1 to 3 m/s and an average air temperature of 30°C, representing urban conditions typical of cities such as Medan. Simulation outputs included airflow velocity, pressure distribution, and potential temperature reduction. In addition, the potential for natural daylight exposure in the planting

zones was analyzed using the Ladybug Tools plugin for Rhinoceros, enabling the mapping of solar radiation on wall surfaces.

The evaluation criteria for each design encompassed three main aspects:

- Airflow efficiency, determined from CFD simulation results.
- Suitability as planting media, evaluated based on soil capacity and access to sunlight.
- Aesthetic quality, assessed through visual evaluation by expert respondents and architecture students.

The results of these three aspects were compared using a performance matrix to identify the most optimal design.

3 Results and Discussion

The simulation and evaluation of various green ventilation block (GVB) models revealed significant performance variations depending on geometric form and the proportion between ventilation areas and planting spaces.
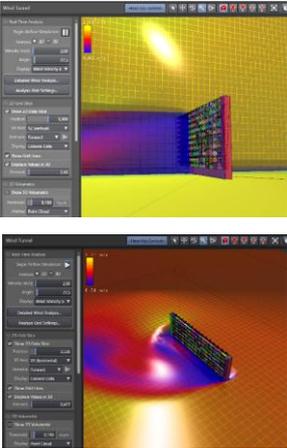
Table 1. Various green ventilation block (GVB) models

| Model 1	Model 2	Model 3
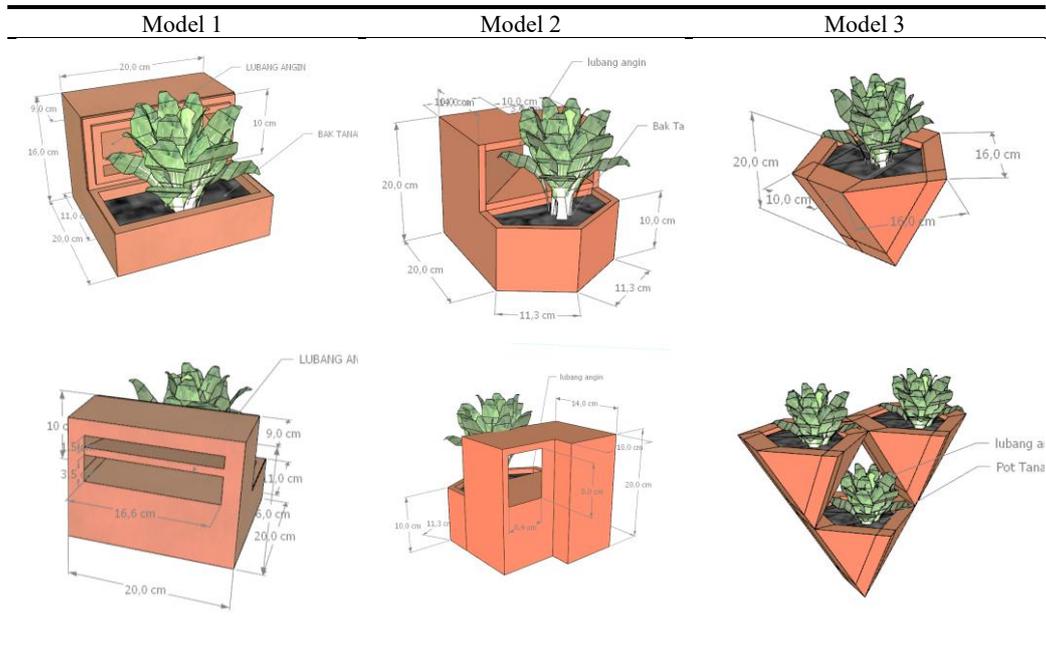
Wind Analysis

Wind analysis using Computational Fluid Dynamics (CFD) assessed airflow velocity, pressure distribution, and turbulence under tropical conditions (wind speeds 1–3 m/s, temperature 30°C). Results showed that geometry and opening orientation strongly affected airflow patterns. GVB-03 achieved the best performance with smooth circulation and a peak velocity of 2.3 m/s, while GVB-01 and GVB-02 created higher resistance and uneven air movement. This highlights the role of optimized block geometry in enhancing passive ventilation efficiency.

Table 2. Wind Analysis

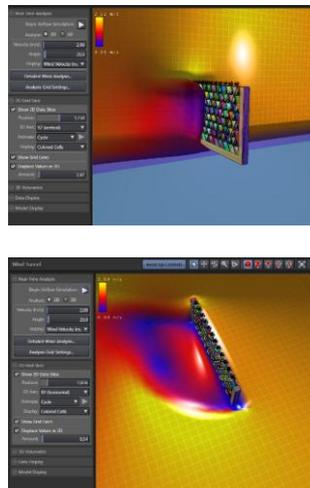| Model GVB	Wind Simulation (Vertical/Horizontal)	Result
Model 1		Model GVB-01 (symmetrical inlet and outlet of equal size but with relatively small openings) tended to produce poor airflow contribution and less effective ventilation.

Model 2
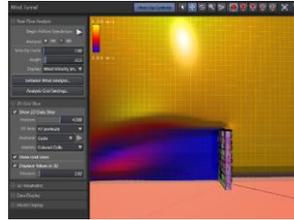
Model GVB-02 (smaller inlet compared to the outlet) exhibited less efficient air circulation and indicated higher resistance to airflow.

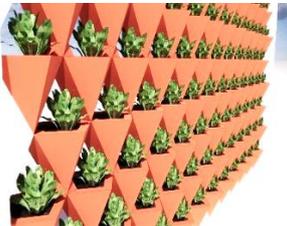| Model GVB	Wind Simulation (Vertical/Horizontal)	Result
Model 3	 	**Model GVB-03** (inverted pyramid design with diagonal openings) demonstrated the highest airflow velocity. This design also showed stable pressure distribution, enabling uniform air intake without excessive turbulence.

Sunlight Analysis

In terms of natural lighting for plants, GVB-03 with triangular openings and specific angled orientation recorded the highest solar radiation exposure among all models, ranging from 350–

420 Wh/m² per day. This suggests that opening orientation significantly influences direct sunlight penetration into planting zones, which is critical for vegetation growth. By contrast, GVB-01 and GVB-02 produced more shading, leading to reduced sunlight in planting areas and potentially limiting plant development.
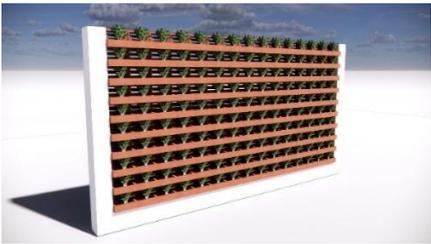
Table 3. Sunlight Analysis

Model GVB	Shading Analysis at 10.00 am	Result
Model 1		For GVB-01, heavy shading occurred across almost all block levels

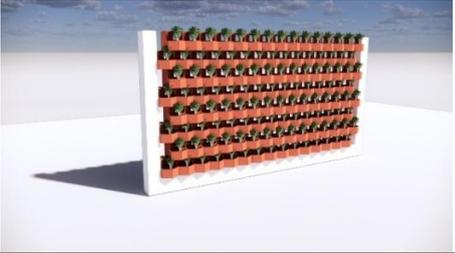| Model GVB	Shading Analysis at 10.00 am	Result
Model 2		For GVB-02, shading was significant on odd-numbered block levelswhile even-numbered levels received sufficient sunlight
Model 3		For GVB-03, shading was minimal across all block levels, allowing adequate sunlight penetration

Regarding planting feasibility, GVB-01 had a planting volume of 154 cm³ with a depth of approximately 6 cm, making it less ideal for plants with medium to deep root systems. GVB-02 provided 130 cm³ of planting volume with a depth of about 10 cm. GVB-03 offered the largest planting volume of 190 cm³ with a depth of around 20 cm (narrowing inward), providing more suitable conditions for root development.

Aesthetic Evaluation

In terms of aesthetics, the evaluation results highlighted notable differences among the three green ventilation block (GVB) models. Assessments were conducted with both professional architects and architecture students, focusing on three key aspects: visual attractiveness, design dynamism, and ease of integration into building façades. The findings revealed that GVB-03 was the most favored model, consistently praised for its innovative form, dynamic geometry, and compatibility with modern façade design. It received the highest average score of 4.5 out of 5.0, reflecting strong visual appeal and adaptability. GVB-02 also performed relatively well, with an average score of 3.2, mainly due to its balanced proportions and moderate dynamism, though some respondents noted that its smaller inlet reduced visual rhythm. Meanwhile, GVB-01, despite being structurally simple and modular, was considered monotonous and less engaging visually, earning the lowest score of 1.5. These results underscore the importance of aesthetic considerations in sustainable architectural components, where functional performance must be complemented by visual quality to ensure broader acceptance in practice.

Table 4. Aesthetic Evaluation of Green Ventilation Block Models

Model	Average Score (1–5)	Strengths	Weaknesses	Overall Perception
GVB-01	1.5	Simple, modular, easy to replicate	Monotonous, lacks visual interest, limited façade appeal	Least attractive, functional only
GVB-02	3.2	Balanced proportions, moderately dynamic,	Smaller inlet reduces rhythm,	Acceptable but less striking

			integrates fairly well	less distinctive	
	GVB-03	4.5	Dynamic geometry, innovative form, high visual appeal, strong façade integration	Slightly more complex to produce	Most attractive and preferred
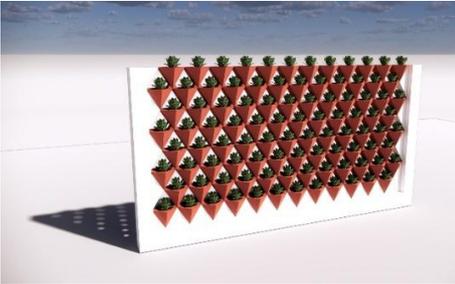
When all results were compared using a performance matrix, GVB-03 emerged as the most balanced design, integrating aesthetics, ventilation efficiency, and planting potential. This model demonstrated strong airflow performance, sufficient plant lighting, and visually attractive form. These findings highlight that the development of ventilation block designs must consider not only technical aspects but also the integration of ecological function and visual quality within the framework of sustainable tropical architecture.

Overall, this study reinforces the importance of an integrative approach to passive building element design. Shape and material innovation in green wall ventilation blocks can significantly contribute to energy savings and improvements in micro-environmental quality, particularly in tropical urban areas with high pollution and temperature levels.

4 Conclusion

his study evaluated the performance of different green ventilation block (GVB) models designed to support passive ventilation strategies and green wall systems in sustainable tropical buildings. Using a parametric design approach and Computational Fluid Dynamics (CFD) simulations in Autodesk Vasari, each model was assessed based on three main criteria: airflow efficiency, planting quality (light and growing medium), and aesthetic value as a façade element.

The simulation results showed that geometry and opening orientation significantly affect ventilation performance and natural light exposure. Among all tested models, GVB-03

produced the most optimal overall results: efficient airflow, stable pressure distribution, sufficient plant lighting, and strong visual appeal according to expert evaluations. These findings emphasize the importance of integrating technical, ecological, and aesthetic functions in green building element design.

In general, this research demonstrates that eco-friendly ventilation block innovations hold strong potential to advance adaptive and sustainable tropical architecture. The main recommendation is the adoption of performance-based design approaches from the early stages of development, with consideration for modular GVB applications in housing, schools, and public facilities within hot and humid climates.

Future research should explore full-scale experimental testing, performance across various plant species, and the integration of irrigation and water management systems to support the long-term sustainability of micro-ecosystems in modular green walls.

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