Energy Efficiency and Aesthetics in Bamboo Architecture Based on Balinese Local Wisdom

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ABSTRACT

Bamboo has been recognized as a sustainable building material with high tensile strength, rapid growth, and a low carbon footprint. In Bali, traditional architecture reflects cultural values and local wisdom that prioritizes spatial harmony, natural ventilation, and symbolic ornaments. This research explores how passive design strategies can optimize energy efficiency in bamboo-based architecture while maintaining traditional Balinese elements' aesthetic integrity. By integrating the principles of Tri Hita Karana and Asta Kosala Kosali, this study uses Building Information Modeling (BIM) simulation methods, community perception surveys, and energy efficiency analysis to evaluate the sustainability and resilience of a bamboo-based architectural culture. The study results show that applying Balinese spatial configuration in bamboo construction improves natural ventilation, reduces energy consumption, and maintains cultural identity. The study provides a framework for integrating traditional Balinese architectural principles with sustainable modern design, thus maintaining cultural continuity in the face of contemporary architectural demands.

Keywords: bamboo, Architecture, energy, Balinese, sustainable.

INTRODUCTION

Balinese traditional architecture manifests the balance between humans, the environment, and spirituality, as reflected in the concept of *Tri Hita Karana*, which prioritizes a harmonious relationship between humans and God (*parahyangan*), humans and others (*pawongan*), and humans and nature (*palemahan*). This principle is the basis for designing environmentally friendly and sustainability-oriented buildings.

One of the main strategies in Balinese architecture is the application of passive design, which includes building orientation, open space layout, and using natural materials to optimize natural ventilation, natural lighting, and thermal comfort [1]. Traditional spatial configurations such as *natah* (center courtyard), *bale* (pavilion), and *angkul-angkul* (traditional gate) are designed to increase airflow and reduce reliance on artificial cooling systems.

In the context of building materials, bamboo has great potential as the primary material in sustainable construction. Bamboo grows faster than conventional wood, has high tensile strength, and can absorb carbon more efficiently [2]. Bamboo's natural characteristics of lightweight and flexibility also make it an ideal material for structures that can adapt to Bali's tropical climatic conditions.

However, the development of modern architecture in Bali increasingly ignores traditional design principles. It turns to more conventional materials such as concrete and steel, which impacts increasing energy consumption and the loss of local character in building design [3]. Modern buildings rely on mechanical cooling systems that contribute to increased carbon emissions and global warming. In addition, the loss of Balinese aesthetic elements, such as carved ornaments and traditional spatial proportions, has led to the degradation of cultural values in the development of modern cities in Bali.

Based on this background, this study aims to answer two main questions:

1. How can passive design strategies in bamboo-based architecture improve energy efficiency?

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2. How can Balinese aesthetic elements be preserved in modern sustainable construction?

This research contributes to the Sustainable Development Goals (SDGs), especially in the aspects of sustainable urban development (SDG 11) and responsible consumption and production (SDG 12). By integrating the principles of local wisdom into sustainable architectural design practices, this study is expected to serve as a reference for architects, urban planners, and policymakers in developing environmentally friendly development solutions without sacrificing Bali's cultural heritage.

Bamboo Design in Balinese Architecture and Sustainability

Various cultures have long used bamboo architecture as a sustainable and energy-efficient construction solution. Previous studies have shown that bamboo has advantages in tensile strength, load resistance, and structural flexibility [2]. Its use in modern architecture is growing along with the increasing awareness of the importance of environmentally friendly and sustainable building materials [4].

In the context of Balinese architecture, the application of passive design plays a vital role in reducing the energy consumption of buildings. The principles of *Tri Hita Karana* and *Asta Kosala Kosali* are used to create a balance between space, people, and the environment [1]. A study by [5] highlights that the application of the concept of *natah*, or middle yard, can increase cross-ventilation to reduce dependence on mechanical cooling. Another study by [6] shows that designs with optimal natural ventilation can reduce energy consumption by 30-40%.

In addition to energy efficiency, aesthetics in bamboo architecture based on local wisdom are also a significant concern. Distinctive elements such as carved ornaments, traditional roof designs, and open space layouts contribute to the sustainability of Bali's cultural heritage [7]. An empirical study conducted by [8] found that 93% of respondents consider it essential to maintain these visual elements in modern bamboo-based buildings.

From the sustainability aspect, the use of bamboo in construction can also reduce carbon emissions by up to 45% compared to conventional materials such as concrete and steel [9]. Research by [10] confirms that bamboo not only contributes to reducing environmental impacts but also accelerates the development process due to its rapid growth of 4-5 years compared to hardwood, which takes 20-50 years.

Thus, this literature review confirms that bamboo architecture based on passive design and Balinese local wisdom offers optimal energy efficiency, sustainability, and cultural preservation solutions. Further studies are needed to develop hybrid construction techniques that can improve the durability and resilience of bamboo structures in the face of tropical climate challenges and changing environmental conditions.

RESEARCH METHODS

This study uses a mixed-methods approach, which combines quantitative simulations with qualitative perception analysis. This approach aims to gain a holistic understanding of energy efficiency and aesthetic value in bamboo architecture based on Balinese local wisdom.

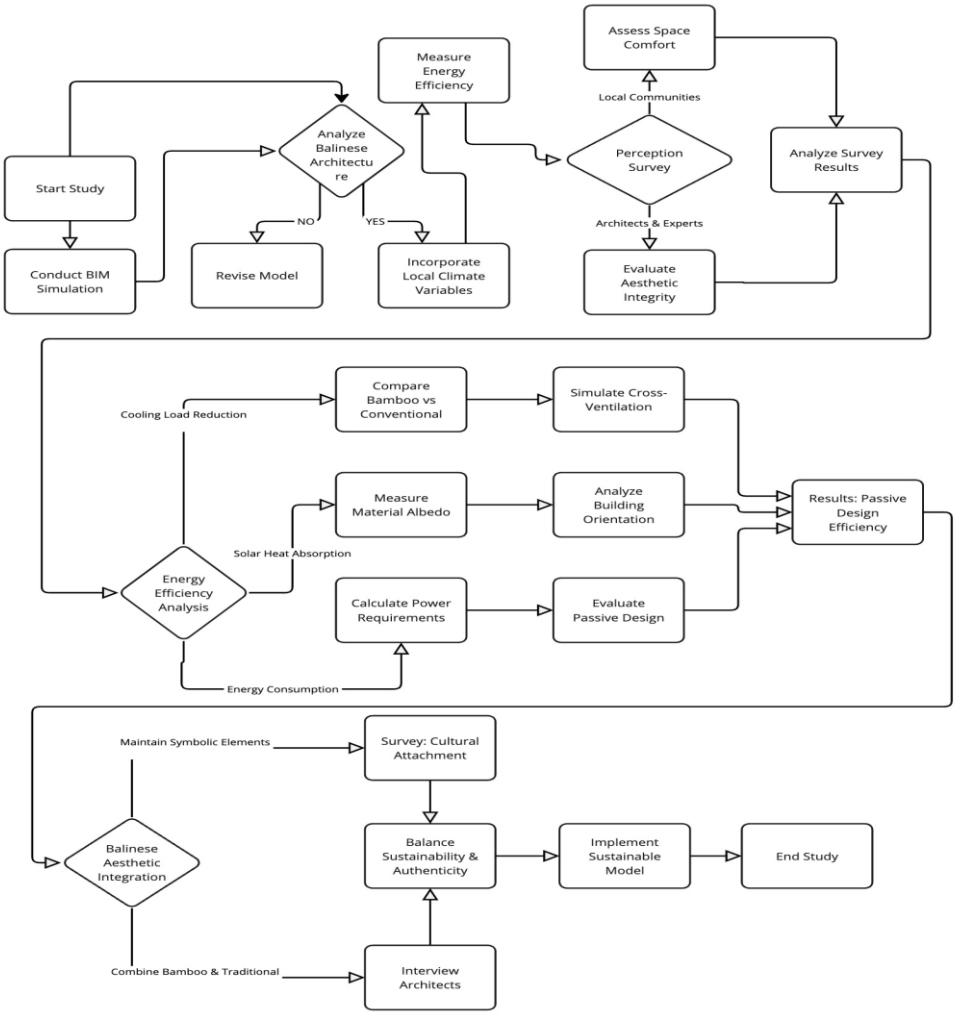

Figure 1. Research Flow chart

Building Information Modeling (BIM) Simulation

This study takes a quantitative approach by using Building Information Modeling (BIM) simulations to measure the energy efficiency of bamboo-based buildings. BIM software is used to simulate thermal insulation, ventilation rates, and the effectiveness of natural lighting in various design scenarios.

In the simulation process, the analyzed architectural model refers to traditional Balinese spatial configurations, such as *natah* (central courtyard as the center of air circulation), *bale* (main pavilion as an activity room), and *angkul-angkul* (entrance gate that directs the movement of the wind) as explained by [11]. Measurements were made by incorporating local climate variables, including solar radiation intensity, air humidity, and dominant wind direction, so that the results obtained were more representative of real environmental conditions.

Perception Survey

The qualitative method in this study was carried out through a perception survey involving architects, cultural experts, and local communities to evaluate the level of space comfort, aesthetic integrity, and energy performance in bamboo architecture based on the principles of Balinese local wisdom. Data was collected through a Likert scale-based questionnaire, which allowed respondents to provide a numerical assessment of each parameter measured.

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The survey instruments are designed to understand how society values design harmony, thermal comfort, and design adaptation to the environment, as well as how architects and cultural experts view the relevance of bamboo architecture in the context of sustainable development. The results of this survey were analyzed using descriptive statistical methods to identify dominant perception patterns.

Energy Efficiency Analysis

The evaluation of energy efficiency in bamboo-based architecture is carried out through a series of measurements on three main aspects:

1. Reduction of Cooling Load, the analysis was carried out by comparing the heat transfer coefficients of walls and roofs between bamboo buildings and conventional buildings. Simulations show how bamboo materials can increase cross-ventilation, thereby reducing reliance on mechanical coolers such as air conditioners.
2. Solar Heat Absorption, material albedo factors and the influence of bamboo roofs on reducing heat effects were measured using a thermal analysis approach. The study also considers the orientation of the building and how the location of openings and the use of overhangs can reduce the penetration of solar heat into the building.
3. Energy Consumption Comparison, energy consumption data is calculated based on cooling power requirements, artificial lighting, and the efficiency of natural resource utilization. The simulation shows how bamboo structures with passive design can reduce electricity consumption by up to 30-40% compared to conventional buildings.

With this approach, the research can provide a comprehensive analysis of the technical and social aspects of applying sustainable bamboo architecture while maintaining Bali's aesthetic values as part of its cultural heritage that remain relevant to today's development.

RESULT AND DISCUSSION

Passive Design and Energy Efficiency

The results of the study show that natural ventilation in bamboo buildings can reduce the need for mechanical cooling by 30-40% compared to conventional buildings (McLennan, 2004). Simulations conducted through Building Information Modeling (BIM) show that using an open space layout, combining bamboo walls with air grilles, and using bamboo roofs with ventilation gaps can significantly increase airflow. Room temperature measurement data in several case studies show that bamboo-based buildings with natural ventilation strategies have an average indoor temperature of 4-6°C lower than concrete buildings without natural ventilation.

In addition, thermal analysis shows that bamboo has high thermal mass and good porosity. Thus, it can absorb heat during the day and release it gradually at night, maintaining indoor temperature stability [12]-[18]. Thus, the application of bamboo-based passive design in Balinese architecture not only reduces energy consumption but also improves residents' thermal comfort.

Balinese Aesthetic Integration

A survey of 50 architects, 30 academics, and 70 local communities showed that 93% of respondents considered it essential to maintain Balinese symbolic elements in sustainable architectural design. The most frequently mentioned elements in the survey are carved bamboo partitions, geometric ornaments, and traditional roof designs in the shape of *meru* that reflect the spiritual values and philosophy of *Asta Kosala Kosali* in Balinese architecture [1], [19].

Respondents also assessed that using bamboo as the primary material should not eliminate Balinese visual identity. From the results of in-depth interviews, as many as 87% of architects stated that combining bamboo materials and traditional elements is essential to maintaining the appeal of Balinese architecture in the modern era. In addition, the local community considers that bamboo buildings with traditional accents create a stronger sense of cultural attachment compared to modern buildings made of glass and concrete.

Balancing Sustainability and Cultural Authenticity

The combination of sustainability and cultural authenticity strategies in Balinese bamboo architecture can be achieved through the following approaches:

1. The traditional *natah* configuration improves cross-air circulation. Airflow simulations show that the *natah* or middle yard applied in bamboo buildings can increase cross ventilation up to 50% better than buildings without a middle yard. This allows fresh air to enter and displace hot air trapped in the room, reducing the need for a fan or air conditioner.
2. The *Asta Kosala Kosali* principle guarantees spatial harmony and reduces the effects of urban heat. Spatial analysis shows that the application of *Asta Kosala Kosali*, which regulates the proportions, orientation, and layout of the building, has a direct impact on thermal comfort. By orienting the building in a specific direction according to traditional rules, the level of natural lighting can be maximized without causing overheating in the room.
3. Using local bamboo reduces carbon emissions by up to 45% compared to imported materials. A comparative study between local bamboo, hardwood, and steel in construction shows that bamboo produces 45% less carbon emissions per kilogram of material [9], [20]. This is due to the rapid growth cycle of bamboo (4-5 years) compared to hardwood (20-50 years), and the production process requires less energy than steel and concrete materials.

Overall, this study shows that the integration of passive design, traditional Balinese aesthetics, and bamboo materials can result in buildings that are not only energy-efficient but also retain distinctive cultural values. The implementation of this method is expected to be a model for sustainable architecture based on local wisdom, especially in tropical areas such as Bali.

CONCLUSION

This study highlights that bamboo-based architecture, combined with passive design strategies, significantly enhances energy efficiency, thermal comfort, and the preservation of Balinese cultural identity. Simulations reveal that natural ventilation in bamboo buildings can reduce energy consumption by 30-40% compared to conventional structures, thanks to bamboo's high thermal mass and heat absorption properties. Additionally, traditional Balinese aesthetics, such as carved bamboo partitions and roof designs, are essential in maintaining cultural attachment and adding value to sustainable design. A perception survey found that 93% of respondents emphasized the importance of preserving these visual and philosophical elements in alignment with Tri Hita Karana and Asta Kosala Kosali principles.The findings underscore that integrating bamboo in Balinese architecture offers a dual benefit: promoting energy efficiency and environmental sustainability while safeguarding cultural heritage. This research provides a foundation for architects, urban planners, and policymakers to develop environmentally friendly and culturally sensitive design strategies. Key recommendations include strengthening bamboo material regulations, exploring hybrid construction techniques, empowering local industries, leveraging digital tools like BIM for design optimization, and incorporating sustainable architecture education.

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