

Research Article

Low-Carbon Strategies in Traditional Vernacular Architecture: A Case Study of Bale Mangina in Senaru, North Lombok, Indonesia

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Article Info	Abstract
Article History	Traditional vernacular architecture provides sustainable design solutions that can contribute to global initiatives aimed at reducing carbon emissions. This study examines low-carbon construction techniques and passive design strategies in Bale Mangina, a traditional residence in Senaru, North Lombok, Indonesia. Using qualitative research methods, including field observations, interviews, and literature reviews, the study identifies key sustainability principles in materials selection, construction practices, and climate-responsive designs. The results show that the use of local bamboo and reed roofs can reduce embedded carbon emissions by up to 45% compared to conventional materials. Passive cooling strategies, including natural ventilation and thermal insulation using organic materials, maintain indoor temperatures within the range of 26–29°C, thereby enhancing thermal comfort and reducing cooling energy requirements by up to 35%. These findings suggest that traditional building techniques can serve as a sustainable model for modern, low-carbon architecture. Future studies should focus on integrating modern technological advances with local wisdom to improve low-carbon construction.
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1. Introduction

Traditional architecture has become an integral part of human civilization's development, offering design solutions that are in harmony with nature and grounded in the principles of sustainability. Many traditional buildings utilize natural materials and employ construction techniques that adapt to local climatic conditions, making them early examples of sustainable architecture [1]. However, in an era of increasingly rapid globalization and urbanization, traditional architecture faces major challenges in terms of sustainability and the preservation of cultural heritage [2].

Urban transformation, often oriented towards economic efficiency, tends to replace the traditional

buildings with modern designs that overlook environmental considerations and local wisdom [3]. This transformation results in the loss of passive design elements that have been demonstrated to enhance thermal comfort without necessitating additional energy consumption [4]. Therefore, an innovative approach is needed that integrates traditional architectural values with modern green technologies without compromising historical and cultural integrity.

One of the primary global challenges today is climate change, driven by rising greenhouse gas emissions resulting from human activities. According to the Intergovernmental Panel on Climate Change (IPCC), the construction and building sectors are responsible for more than 39% of total global carbon emissions, which include emissions from construction processes, building operations, and demolition [5]. Buildings contribute significantly to these emissions through operational energy consumption and the embodied carbon found in construction materials such as concrete and steel [6].

This situation highlights the importance of adopting sustainable design and construction practices to mitigate climate change. One such approach is the adoption of low-carbon architecture, which emphasizes the use of local materials, passive design strategies, and efficient, resilient construction systems [4]. Traditional architecture, with its time-tested practices, offers empirical models that can guide such sustainable development efforts.

A relevant example of this can be found in the traditional dwellings of the Sasak people on the island of Lombok. Their architecture, particularly the Bale Mangina house type in Senaru Village, reflects climatic adaptability and embodies local wisdom [7]. These houses, constructed from bamboo, wood, and alang-alang (thatch) roofs, employ passive design strategies such as cross-ventilation and thermal insulation to achieve thermal comfort without requiring mechanical energy input [8]. Despite the increasing number of tourist visits to Senaru, the architectural integrity of Bale Mangina has largely been preserved [9-11].

However, there has been limited scientific analysis specifically exploring the carbon reduction and sustainability aspects of Bale Mangina's design and construction. This gap justifies the need for further investigation into how traditional Sasak architecture integrates low-carbon design strategies.

Therefore, this research aims to:

- Identify the low-carbon design principles applied in the construction of Bale Mangina in Senaru.
- Assess the contribution of local materials in reducing carbon emissions in traditional Sasak architecture.

- Evaluate how passive design strategies enhance thermal comfort and energy efficiency.
- Explore the implications of these findings for the development of sustainable architectural practices in Indonesia.

Through this study, it is hoped that a deeper understanding will be gained of how traditional architecture can serve as a practical model for sustainable, low-carbon development.

2. Literature Review

The link between traditional architecture and sustainability has been well-documented in scholarly literature. Traditional buildings, developed through generations of empirical knowledge, are often tailored to local climates and built using readily available materials, making them inherently sustainable [1, 2]. Such architecture typically exhibits passive design features such as natural ventilation, shading, and high thermal mass, which enhance occupant comfort while reducing energy demands [4, 12].

Studies on vernacular architecture in tropical climates, including Indonesia, demonstrate that design strategies such as elevated floors, wide overhangs, and ventilated walls significantly improve thermal comfort [12]. These features reduce indoor temperatures and minimize the need for mechanical air conditioning, thus lowering energy consumption. Passive design is particularly relevant in low-income or rural communities, where energy access may be limited and environmental conditions demanding.

In addition to design strategies, the choice of materials plays a critical role in the sustainability of traditional architecture. Research indicates that using locally sourced, low-embodied energy materials, such as bamboo, earth, and thatch, not only reduces carbon emissions but also supports local economies and preserves cultural practices [6, 13]. In the Sasak context, bamboo and alang-alang are abundant, rapidly renewable, and offer effective thermal and acoustic insulation [8].

However, modernization and urban expansion have led to the decline of many traditional building practices. Urban development policies often favor concrete and steel construction, which increases embodied carbon and erodes local identity [3]. Nonetheless, some traditional settlements, like Senaru Village in Lombok, have retained their architectural character despite pressures from tourism and modernization [9-11]. The Bale Mangina house, in particular, continues to demonstrate cultural resilience and ecological performance.

While the socio-cultural value of traditional architecture has received substantial attention, fewer

studies have systematically assessed its environmental performance using metrics like carbon emissions or thermal efficiency [2]. Existing research tends to be descriptive or anthropological in nature, leaving a gap in performance-based evaluations. Furthermore, the integration of traditional architectural principles into contemporary sustainable design frameworks remains underdeveloped.

This literature review reveals that although the environmental potential of traditional architecture is increasingly acknowledged, there is a lack of detailed studies focusing on low-carbon performance, particularly within the context of Sasak architecture. As such, this research contributes to bridging the gap between vernacular traditions and modern sustainable architectural practices by providing empirical insights into the low-carbon features of Bale Mangina.

3. Materials and Methods

3.1. Research Approach

The research approach used in this study is an exploratory qualitative approach, which aims to explore the phenomenon of *Bale Mangina* design and construction in depth [14]. This approach enables researchers to gain a more comprehensive understanding of how local communities construct and maintain their traditional homes within the context of environmental sustainability. An analysis was conducted to assess the contribution of these buildings to reducing energy consumption and carbon emissions, examining aspects such as architectural design, material utilization, and passive energy strategies.

3.2. Data Collection Techniques

To obtain valid and accurate data, this study combines primary data and secondary data through the following methods:

1. Primary Survey (Field Observation and In-Depth Interview). Field observations were carried out directly in Senaru Traditional Village, Bayan District, North Lombok Regency (Figures 1 and 2). This technique is used to document the physical characteristics of *Bale Mangina*'s buildings, including their spatial layout, dimensions, types of materials used, and passive design elements applied [15]. Observations also include area maps, satellite maps, and two-dimensional maps of existing facades to obtain a clearer spatial understanding. In addition to observation, this study also uses an *in-depth interview* method with three sources who are the owners of *Bale Mangina*'s house and are considered representative of this study. The interview aims to delve deeper into the design philosophy, material selection, and residents'

experiences related to thermal efficiency and building sustainability [16].

2. Secondary Survey (Literature Study and Document Analysis). Secondary data were collected through a literature review and document analysis related to traditional Sasak architecture, sustainable design, and principles of low-carbon architecture. Literature sources include scientific journals, books, research reports, and official documents that discuss environmental and material aspects of sustainable materials in traditional architecture. This study also draws on references from green building standards, such as Greenship from the Green Building Council Indonesia [17] and *the concept of Net Zero Energy Building* (NZEB) from the World Green Building Council [5].

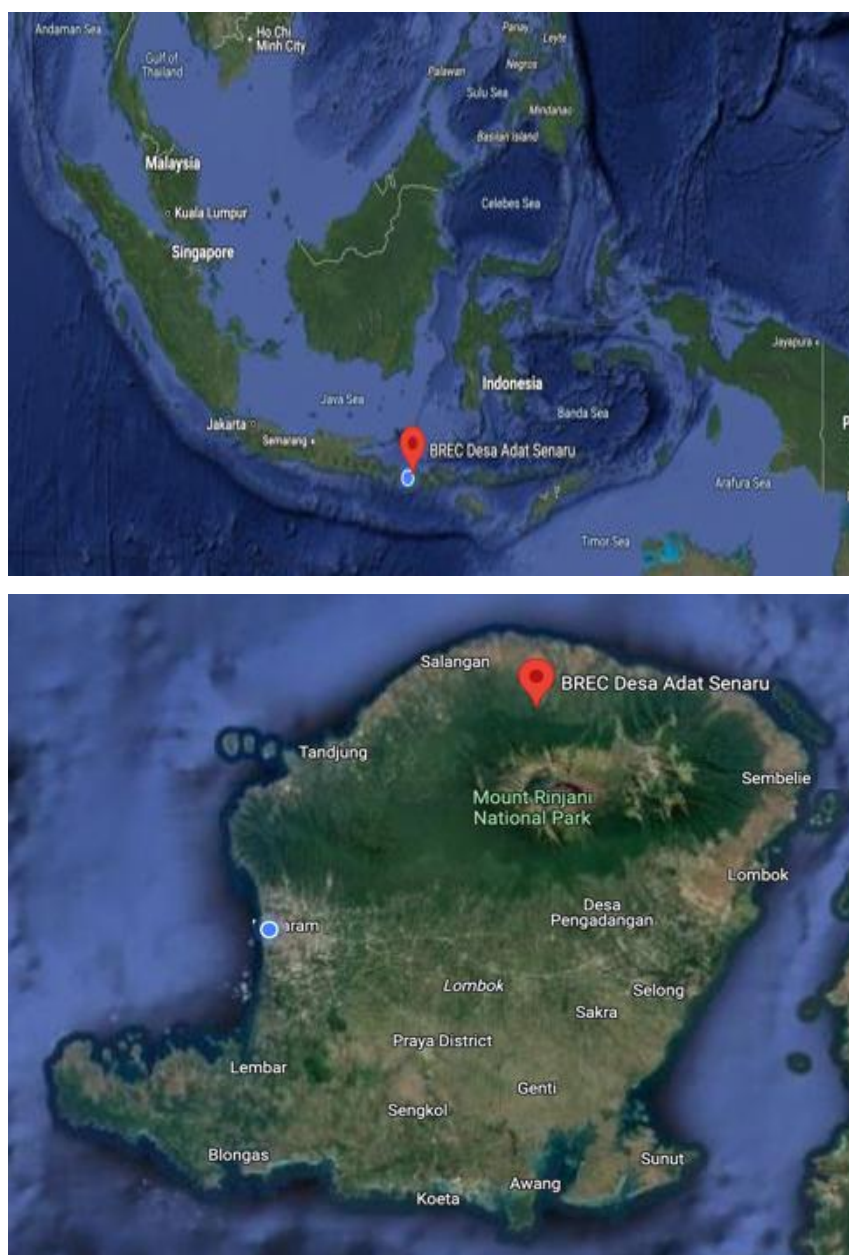


Figure 1. Location Point of Senaru Traditional Village, North Lombok, Indonesia (Source: Google Maps, 2025)



Figure 2. Satellite View of Senaru Traditional Village, North Lombok, Indonesia (Source: Google Maps, 2025)

3.3. Data Analysis Methods

The collected data is analyzed qualitatively to identify patterns in the use of local materials, passive design strategies, and the effectiveness of buildings in optimizing thermal comfort. The analysis is carried out through the following stages:

1. Morphological Analysis and Architectural Typology. This analysis was conducted by examining the layout, orientation, and spatial relationship of Bale Mangina with its surrounding environment. This study compares design elements with the principles of *low-carbon architecture* to understand how these traditional buildings can be categorized as green architecture that is adaptive to the tropical environment [18].
2. Materials and Passive Energy Analysis. This analysis focuses on the role of local materials, such as bamboo and weeds, in reducing embodied carbon, as well as the efficiency of passive design strategies, including cross ventilation, the use of porous roofs, and natural insulation, in maintaining thermal comfort without high energy consumption [19]. The use of materials with *low embodied energy, compared to conventional materials such as concrete and steel, is also evaluated through the Life Cycle Assessment (LCA) approach* to measure the carbon impact of the construction and operational processes of buildings [20].
3. Thematic analysis of the interview results. The data obtained from the interviews were analyzed using a *thematic analysis* method to identify patterns in people's understanding of sustainability and their construction practices [21]. This analysis aims to understand residents' perceptions of the effectiveness of passive design in reducing reliance on artificial refrigeration as well as the sustainability of the materials

used in the construction of their homes.

4. Comparison with Previous Studies. The results of the study were compared with previous studies related to green architecture and sustainability in traditional housing. References from previous research on traditional houses in Penglipuran Village, Bali [22], and Sade Village, Lombok [2], were used as comparisons to identify patterns of similarities and differences in the application of low-carbon design principles across various regions of Indonesia.

4. Results and Discussion

4.1. Senaru Traditional Settlements: Context and Characteristics

Senaru Traditional Village is a traditional settlement situated in North Lombok Regency, West Nusa Tenggara Province, and is located within the Mount Rinjani National Park (TNGR) area (Figures 1 and 2). As one of the tourist villages on the island of Lombok, this village boasts a strong cultural appeal, particularly in the form of traditional settlements that retain their original architectural and spatial forms.

This uniqueness makes Senaru a popular destination visited by many domestic and international tourists. Access to the village is limited to private motorized vehicles, as there is no public transportation network directly connected to the settlements. To maintain the preservation and comfort of the environment, motor vehicle parking is provided outside the village, allowing tourists to explore the area on foot. An overview of the village layout is shown in Figure 3.

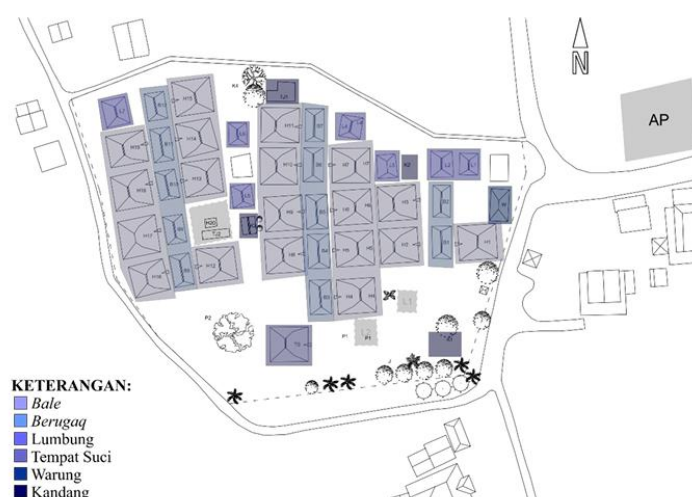


Figure 3. The traditional settlement pattern of Senaru (Source: Master of Architecture Program [23])

As a traditional settlement situated on the slopes of Mount Rinjani, ecological factors and geographical conditions significantly influence the shaping of spatial patterns and environmental adaptation strategies. Mount Rinjani is not only a geographical feature that dominates the landscape but also holds spiritual

significance for the local people, who consider it the center of the cosmos in their traditional beliefs [24]. This cosmological concept directly influences the orientation of settlements that generally face north and south, reflecting the balance between mountains and oceans. Winds blowing from the south bring moisture and fertility that support the agricultural sector and maintain the balance of local ecosystems [25].

As part of the vernacular architecture, settlements in Senaru Village have evolved over generations, taking into account environmental factors and the social needs of the local community. Rapoport defines vernacular architecture as a cultural expression reflected in the physical and non-physical forms of buildings built according to the practices of local communities [18]. In the context of Senaru Village, this practice is evident in the selection of natural materials readily available around the village, the layout of buildings that follow the contours of the land, and the adaptation to humid tropical climatic conditions, which allow for maximum natural ventilation in each residence.

The settlement has existed since the 14th century and has grown in tandem with population growth and social development. Initially, there was only one main village, namely Bayan Beleq Village, which later developed into several other settlements, including Senaru and Karang Bajo Villages, which are geographically adjacent to each other. Senaru Village, the focus of this research, comprises several residential buildings and supporting facilities. Based on the survey results, there are 22 residential buildings and several non-residential buildings, including 12 *beruqaq* (multifunctional open buildings) and 7 rice barns, called *sambi* or *geleng*.

The layout of settlements reveals spatial patterns that reflect the social systems and hierarchies within society. *Sambi/geleng*, which functions as a granary for storing crops, is placed on the edge of the settlement, reflecting the importance of food security in the life of the agrarian community. In the southernmost part of the settlement, there is the *amaq* local house, which belongs to traditional elders who are highly respected in the social structure of the Senaru community. Additionally, there is a '*pagan*' (a term from the Sasak/Lombok Language), which is an open space not intended as a residence but used as a center for communal activities, such as traditional celebrations and other social gatherings.

The majority of the residents of Senaru Village are natives who were born and raised in the village, with close kinship ties among them. The community's main livelihood is divided into two sectors: agriculture and tourism. Most residents work in the agricultural sector, managing the gardens located around the village to cultivate food crops and spices. Meanwhile, the tourism sector is also growing rapidly, with

people working as tour guides, community-based lodging managers, and local traders who cater to the various needs of tourists. With the increasing number of tourists visiting Senaru, there are challenges in striking a balance between tourism-based economic development and the preservation of cultural and environmental heritage.

The ecological factors that support the sustainability of these settlements need to be clarified in the context of disaster mitigation and adaptation to dynamic environmental conditions. Topographically, the settlement's position on the mountain slopes provides an advantage in terms of natural air circulation, as the wind moving from the sea to the land helps maintain a comfortable temperature in the residence. Additionally, building layouts that follow the contours of the soil minimize the risk of erosion and optimize land use without disrupting the ecological balance.

From a disaster mitigation perspective, these settlements also take into account the risk of earthquakes and sea winds. Considering that Lombok is an area that often experiences tectonic activity, traditional buildings in Senaru have been designed with structural flexibility, using lightweight materials such as bamboo and wood that can dampen earthquake vibrations. In addition, the use of a porous thatch roof allows for better airflow to enter, reducing the risk of overpressure during strong winds. By understanding this strategy, it can be concluded that Senaru Village is not just a traditional settlement but also a genuine example of environmental adaptation based on local wisdom that can serve as a reference for the development of sustainable settlements.

In conclusion, Senaru Traditional Village plays a crucial role in preserving vernacular architecture that is adaptive to its environment, encompassing spatial planning, social systems, and disaster mitigation strategies. The relationship between settlements and their ecological factors suggests that local communities have developed adaptation patterns that not only preserve their cultural heritage but also enable them to cope with climate change and environmental dynamics in a sustainable manner. Taking these factors into account, this study underscores the importance of understanding traditional spatial systems in sustainable settlement planning in the tropics.

4.2. Bale Mangina as a Sustainable Traditional Residential Model

Bale Mangina is a traditional Sasak residence form in Senaru Village that still maintains the principles of vernacular architecture. This residence is built with the main structure of wooden pillars, a massive foundation, an earthen floor, bamboo walls, and a thatched roof. The structure reflects adaptation to the

tropical environment by taking into account thermal comfort, material sustainability, and energy efficiency. The size of the building is relatively uniform, ranging from 7 to 7.5 meters in width and 8 to 8.5 meters in length, with the foundation and floor raised approximately 0.45 meters above the ground. This design is intended to enhance air circulation beneath the floor and minimize moisture from the ground. This uniformity reflects construction standards that have been passed down from generation to generation, with differences more noticeable in the types of woven bamboo for walls and flooring materials, as well as variations in door and window design (Figure 4).



Figure 4. Front view (left) and rear view (right) of the bale mangina (Source: author's documentation, 2023).

In the initial construction, Bale Mangina did not have windows as additional openings, which aimed to maintain a stable indoor temperature. However, during its development, some houses have undergone changes by adding windows to improve natural lighting and thermal comfort within the building. There are two main orientations in the layout of Bale Mangina in Senaru Village, namely north-south and east-west, although these orientations do not directly affect the spatial organization of the house. Each unit of Bale Mangina is arranged to face one another, creating a communal open space in the middle that fosters a pattern of close social interaction among the residents of the settlement (Figure 3).

From the aspect of space organization, Bale Mangina features an open plan, with space functions divided based on differences in floor elevation. The main rooms in Bale Mangina include sleeping areas, kitchens, storage areas, and sacred areas, known as *inen bale*. The main activities in Bale Mangina are centered on sleeping and cooking, with *the inen bale serving as the core space that holds* spiritual and social value for the residents. The concept of spatial organization reflects the social structure that places women as the main managers of the household, as stated by Anggriani [26], who explains that traditional house design is often designed taking into account the needs of its occupants, including elements that form space, spatial organization, and the relationship between lifestyle and social behavior. However, physical

elements of the house include the arrangement of indoor and outdoor spaces, spatial organization, circulation, and spatial hierarchy [27].

4.2.1. Bale Mangina's Architectural Adaptation to the Principles of Sustainability

As a model of sustainable traditional housing, Bale Mangina demonstrates various adaptation strategies to the tropical climate and environment. One of the main aspects that supports the sustainability of this building is the use of natural materials such as bamboo and weeds obtained from around the settlement. This material has *low embodied energy*, low carbon emissions, and is easy to recycle, making it a more environmentally friendly choice than traditional construction materials like concrete and steel.

The role of thatched roofs and bamboo walls in creating natural ventilation is an important factor in the thermal efficiency of buildings. The roof of the weed has a porous nature that allows hot air to escape easily, thus helping to keep the indoor temperature comfortable even without artificial cooling. The bamboo webbing used on the walls also promotes natural air circulation by allowing wind to enter the house without compromising the occupants' privacy.

In a comparative study with other traditional houses in the tropics, such as the Bugis Stilt House in Sulawesi and the Gadang House in West Sumatra, Bale Mangina exhibits similarities in the use of wooden structures and raised floors, which aim to avoid moisture while improving air circulation. However, the difference lies in the shape of the roof and the wall material. Rumah Bugis and Rumah Gadang feature a more solid main wall constructed from wood, whereas Bale Mangina utilizes bamboo with an open, wicker-like design, allowing for better ventilation without the need for large windows.

4.2.2. Effect of Material Changes on Thermal Efficiency

One of the changes that occurred in the construction of Bale Mangina in Senaru Village was the replacement of dirt floors with cement floors in several buildings. These changes aim to enhance the cleanliness and durability of buildings, while also affecting indoor thermal efficiency.

The ground flooring on the original Bale Mangina has a natural ability to absorb and release heat slowly, helping to maintain a stable room temperature throughout the day. However, with the use of cement flooring, buildings experience an increase in indoor temperature, as cement absorbs heat more quickly and releases it more rapidly, thereby increasing a need for additional ventilation to maintain the thermal comfort of residents. A study conducted by Fathy [19] demonstrated that the ground floor in traditional houses serves as a natural temperature regulator, whereas materials such as concrete or cement tend to create heat

island effects on a micro-scale.

Additionally, the closure of the cages (open spaces in the house) by some residents also alters the natural ventilation pattern within the house. Bale Mangina, which maintains an open coop tends to have cooler temperatures compared to those that have been closed. This suggests that structural modifications can impact the thermal performance of buildings, and therefore, they need to be further considered in efforts to preserve Bale Mangina as a low-carbon residential model.

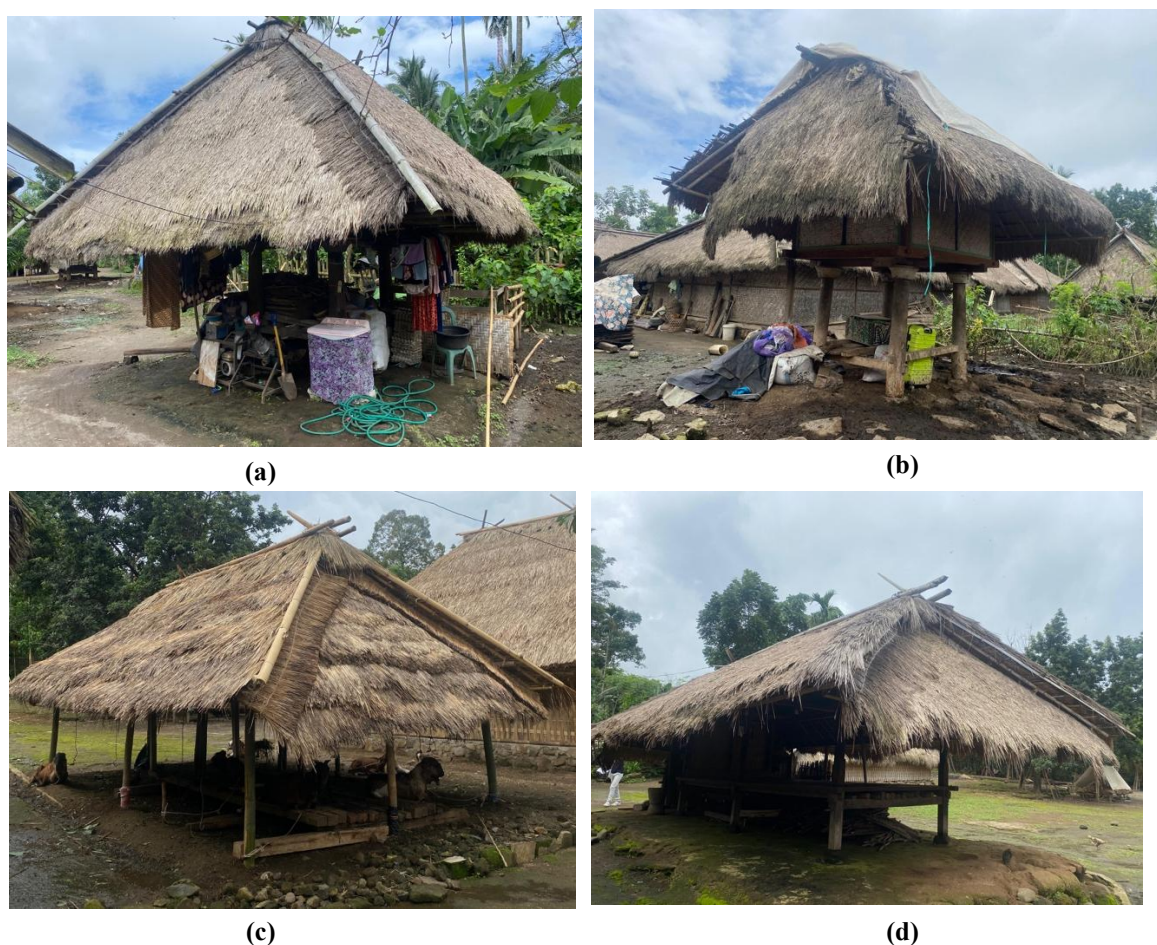


Figure 5. Non-residential functional buildings (a) *geleng*, (b) *sambi*, (c) *berugak*, and (d) livestock drums (Source: researcher documentation, 2025)

4.2.3. The Function of Supporting Buildings in Residential Sustainability

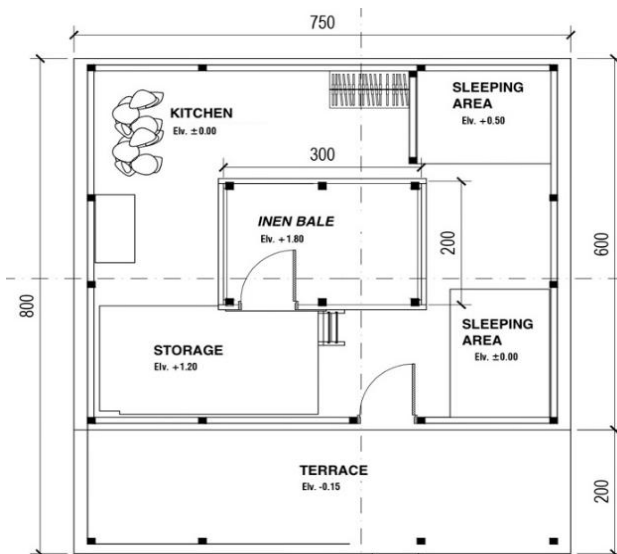
To support the residential function of Bale Mangina, the people of Senaru Village also have several supporting buildings (Figure 5), such as *berugak*, *sambi/geleng* (rice barn), and cattle sheds. *Berugak* is an open structure used to receive guests, socialize, and rest, while *sambi/geshake* functions as a storage place for rice crops. This structure illustrates that the spatial planning system of the Sasak community prioritizes not only individual residences but also economic sustainability and food security.

Sample

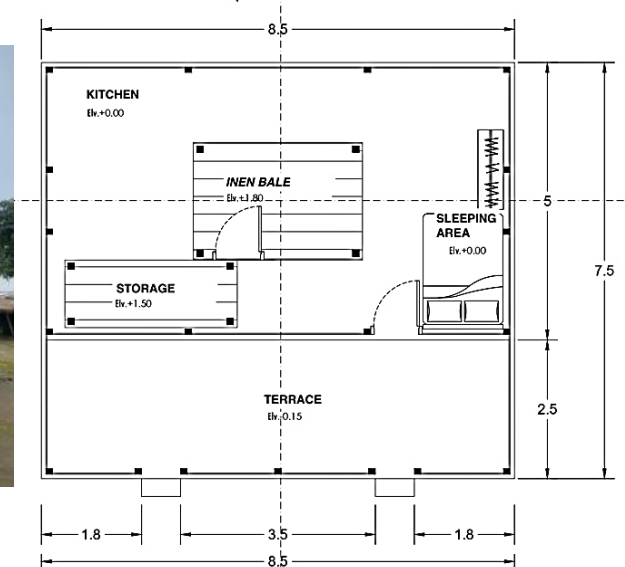
Bale Mangina

Floorplan

S (7)



NU (1)



NA (3)

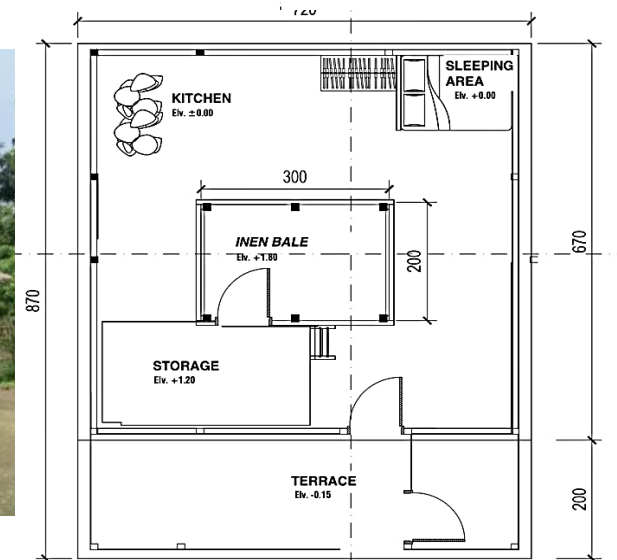


Figure 6. Samples of *bale mangina* (Source: researcher documentation, 2025)

In their daily lives, the basement of the *sambi/geleng* is used as a storage place for firewood taken from the field, while the area under the rice barn is also used as a livestock pen at night. This pattern describes the integration between housing, natural resources, and economic activities, where each element in the settlement system has an ecological role that supports and complements the others.

4.2.4. Observation Results of Bale Mangina in Senaru Village

To gain a deeper understanding of the application of sustainability principles in Bale Mangina, this study observed three sample houses: Mr. S's house (50 years old), Mr. NA's house (51 years old), and Mrs. NU's house (67 years old). Each house has a different number of residents, specifically 7 residents (Mr. S), 3 residents (Mr. NA), and 1 resident (Mrs. NU), as shown in Figure 6.

The results of observations show that the basic structure and spatial organization in Bale Mangina tend to be identical, both in terms of layout and spatial function. The main difference lies in the modifications made to the openings and floor materials, which affect the level of thermal comfort. In the context of sustainability, Bale Mangina maintains green architectural values through the use of natural materials, passive design, and spatial planning systems that support a balance between domestic and social activities.

Taking these factors into account, this study confirms that Bale Mangina is a traditional residential model that can maintain the principles of ecological, social, and economic sustainability, and serves as an example of the development of low-carbon architecture in the tropics.

4.3. Low-Carbon Architectural Strategy at Bale Mangina

Bale Mangina, as part of the traditional Sasak architecture in Senaru Village, embodies development practices that align with sustainability and low-carbon principles. The implemented low-carbon architectural strategies include the use of natural materials with a low carbon footprint, passive design for thermal comfort, and waste management based on the circular economy.

4.3.1. Low Carbon Materials and Building Life Cycles

The materials used in the construction of Bale Mangina are mostly from the surrounding environment, including *rajumas* wood for the main structure, bamboo as a wall element, and reeds as roof materials. The use of these natural materials not only reduces dependence on industrial building materials but also contributes to the reduction of carbon emissions during the construction process. Figure 7 shows the main structure and elements of Bale Mangina, which consisted of a wooden foundation planted directly into the

ground, walls made of woven bamboo (*bedek*), as well as a roof covered by reeds. Bamboo walls have flexible properties that can absorb earthquake shocks, while reed roofs serve as natural insulators, reducing heat loads from the outside.

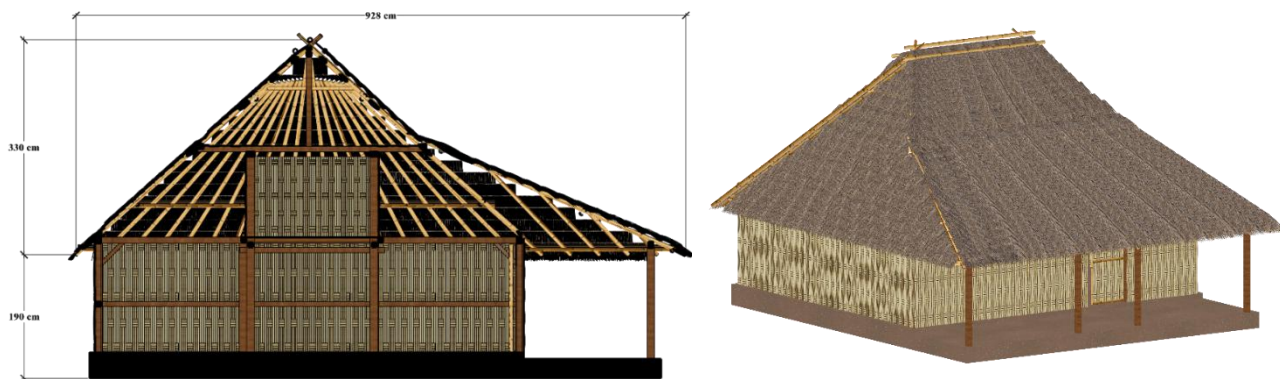


Figure 7. Perspective and Section of Bale Mangina (Source : Gazalba and Saptaningtyas [28].)

In terms of its life cycle, Bale Mangina is designed to last for a long period with minimal maintenance. Structural timber can last up to 25 years, while reed roofs need to be replaced every 5 years. Material changes are implemented through traditional community-based methods, where the community collaborates to help rejuvenate the roof and walls.

Figure 8 shows the process of dismantling and installing the reed roof carried out by the people of Senaru Village. This process demonstrates how the material rejuvenation system in Bale Mangina preserves local values in sustainable architecture, while reducing construction waste by recycling reeds that are still suitable for use in building support.



Figure 8. Restoration of Bale Mangina by the community (Source: informant documentation, 2021)

In addition to considering the life cycle of materials, Bale Mangina also has an efficient natural resource management system. The local community manages a collective garden that provides materials, such as bamboo and reeds, which are then used to build the house's roof without the need to transport

materials from outside the village. The system supports the principle of a circular economy, where materials are utilized in a sustainable cycle, generating minimal waste.

4.3.2. Passive Design Strategies for Thermal Comfort

One of the key strategies in Bale Mangina's design is the application of natural ventilation, which leverages air circulation through bamboo wall gaps and the shape of the reed roof. The saddle-shaped roof structure allows hot air to rise up and out through the gaps, creating a natural cooling effect.

The results of temperature measurements show that the temperature inside the Bale Mangina ranges from 23–28°C, while the outdoor temperature can reach 30°C or more. This demonstrates that this traditional home design is effective in maintaining a stable indoor temperature without the need for artificial cooling.

Figure 9 illustrates the details of the bamboo woven wall structure, which serves as a passive ventilation system, allowing air to flow through small gaps without compromising the occupants' privacy.



Figure 9. Bale Mangina walls still use split bamboo woven material (Source: researcher documentation, 2025)

In addition to natural ventilation, the building's orientation also plays a crucial role in optimizing thermal comfort. Most of the Bale Mangina faces north-south, which helps reduce exposure to direct sunlight during the day. Some houses face east-west, but this position is offset by a reed-roof overhang that helps provide shade and reduce overheating.

Comparisons with other traditional houses, such as Rumah Panggung Bugis and Rumah Gadang, reveal that Bale Mangina features a more open ventilation system, whereas stilt houses rely more heavily on cavities under the floor to regulate temperature. This approach suggests that Bale Mangina is more adaptive to humid tropical climates, where natural ventilation levels take precedence over more enclosed insulation.

4.3.3. Waste Management and Material Conservation

The waste management system in Bale Mangina reflects the principle of a circular economy, where materials that are no longer used can be recycled or returned to nature. Waste reeds, which are no longer used, are often reused as agricultural mulch, while weathered bamboo and wood are utilized as biomass fuel or left to decompose, enriching the soil.

In addition to construction waste, household waste management is also carried out naturally. Organic waste is collected for composting, while non-biodegradable plastic waste is often collected to be taken to landfill. This system can still be improved with a more efficient community-based waste management approach.

Figure 10 shows the use of firewood as fuel in some Bale Mangina. Although many people still use firewood, the use of gas stoves is also increasing as a more practical alternative.



Figure 10. Use of firewood for cooking and gas stoves as an alternative (Source: researcher documentation, 2025)

From the perspective of material conservation, the most significant change in Bale Mangina occurred on the floor of the house. In the past, floors were made from compacted clay; however, many homes are now switching to cement floors. Although more durable, cement flooring has higher thermal conductivity, which makes the house hotter compared to ground flooring.

The waste management approach employed in Bale Mangina can serve as a model for community-based waste management. Some recommendations to improve the efficiency of this system include:

1. The use of used reeds to extend the life cycle of materials.
2. Training on circular-based construction techniques to optimize the reuse of building materials.
3. Improved non-organic waste management with a community-based recycling system.

Bale Mangina, as a sustainable traditional residential model, integrates passive design strategies,

natural materials, and community-based waste management systems to create effective, low-carbon architecture. By adhering to the principles of life cycle assessment, utilizing local materials, and implementing climate-based design strategies, Bale Mangina exemplifies how traditional architecture can contribute to the solution in mitigating climate change and promoting sustainable development.

As a form of adaptation to the changing times, Bale Mangina has undergone several modifications in materials and construction. However, the sustainability values contained in its design and spatial planning remain the main aspects that can be adopted in the development of modern architecture based on low-carbon principles.

4.4. Social and Economic Impact on the Sustainability of Bale Mangina

The sustainability of traditional architecture depends not only on material aspects and design strategies but also on how local communities maintain and adapt to social and economic changes. Bale Mangina, as part of the traditional settlement of Senaru, shows how traditional residential models can survive through social support and adaptation to modern economic dynamics.

4.4.1. The Role of the Community in the Sustainability of Bale Mangina

The people of Senaru Village have a strong social system in place to maintain the sustainability of the Bale Mangina traditional house. Mutual cooperation is a key value in the maintenance and rejuvenation of housing, particularly during the process of replacing materials, such as reed roofs, and repairing wooden structures. This system embodies the principle of vernacular architecture, in which the local community serves not only as users but also as managers of their own architecture [18].

Figure 11 illustrates how the community collaborates in the collective process of building houses. This community-based social structure enables homeowners to maintain the shape and function of Bale Mangina, despite challenges in accessing traditional materials. With this system, maintenance costs are lower because the work is done voluntarily by community members.

However, the main challenge in maintaining the sustainability of Bale Mangina is the shift in preferences among the younger generation. In recent decades, a social shift has occurred, with the younger generation increasingly preferring a modern lifestyle and opting for jobs in the tourism sector over traditional farming or home management. A study by Hidayatun, et al. [29] shows that modernization and globalization often lead to a decrease in interest in preserving traditional architecture, especially in areas that are experiencing increased tourism.



Figure 11. The process of mutual cooperation in the rejuvenation of Bale Mangina (Source: informant documentation, 2021)

However, there are still community efforts to maintain the sustainability of this traditional residence. The Senaru traditional village is a cultural tourism destination, managed by the local community. In addition to efforts to organize traditional settlements, several homestays are designed to resemble the shape of a bale mangina. Designs such as bale mangina allow tourists to experience firsthand life in traditional Sasak houses.

4.4.2. Economic Adaptation and Culture-Based Tourism

Culture-based tourism is one of the main factors that affect the sustainability of Bale Mangina. Along with the development of the tourism sector in North Lombok, Senaru Village has experienced an increase in tourist visits, particularly due to its position as the main route to climb Mount Rinjani. In response to these changes, the community is adapting to meet the needs of tourists. Homestays in the Senaru area have adapted their interior design by incorporating modern amenities, such as private bathrooms and improved lighting. Despite the modifications, the basic principles of using natural materials and traditional structures are maintained to preserve cultural appeal.

Figure 12 shows a homestay with a bale mangina-inspired shape that has undergone some modifications but still retains its traditional elements. This change is a form of community adaptation to economic demands, as well as a way to keep architectural heritage relevant in the modern context.

This approach aligns with the concept of heritage tourism, where the utilization of historic buildings as part of ecotourism can enhance public awareness of preserving their cultural heritage [30]. Some studies suggest that incorporating traditional buildings into tourist attractions can provide an economic incentive for the community to properly maintain and care for them.



Figure 12. Bale Mangina-based homestays that have adapted to modern facilities (Source: documentation researchers, 2025)

However, there are some challenges in this model. The rapid growth of tourism also brings the potential for cultural commercialization, where traditional houses are maintained solely for the sake of tourism without again serving as the primary residence of the local community. To overcome this challenge, several strategies are recommended, including:

1. Strengthening regulations regarding the use of traditional houses as part of sustainable tourism programs.
2. Training for the community on architectural conservation and community-based tourism governance.
3. Diversify the local economy to ensure that people have alternative sources of income beyond tourism.

4.4.3. Social Impact in Bale Mangina's Adaptation to the Changing Times

In addition to the economic aspect, the sustainability of Bale Mangina is also influenced by social changes in the Senaru community. Although some communities still retain traditional practices and cultural values, modernization has brought about numerous changes, particularly in housing patterns and lifestyles.

One of the major changes was the use of modern materials in the construction of Bale Mangina. Many homes are now replacing ground floors with cement or adding glass windows to improve natural lighting. These changes provide additional comfort, but they can also change the thermal properties of the building.

Figure 13 shows one of the modified Bale Mangina, with the use of cement floors and modern windows. While these modifications improve occupant comfort, concerns exist that material changes could compromise the building's natural thermal value and increase its carbon footprint.

The need for durability and comfort often drives material changes in traditional homes, but without consideration for their long-term environmental impact. Therefore, a more holistic approach is necessary for modernizing traditional houses to maintain the principle of sustainability.



Figure 13. Bale Mangina which has undergone modern material modifications (Source: Google Earth, 2016; informant documentation, 2025)

One approach that can be applied is the use of hybrid materials, which is a combination of traditional materials and modern technology that still maintains the sustainability aspect. For example, the development of engineered bamboo materials can be a solution to increase the durability of buildings without sacrificing cultural and environmental values [31].

The sustainability of Bale Mangina depends not only on a low-carbon architectural strategy but also on community support in maintaining traditional social and economic systems. Cooperation and community-based practices have allowed these traditional houses to survive for centuries. However, with social and economic changes, some adaptations are needed to ensure that Bale Mangina remains relevant in the modern era. The tourism sector has had a significant economic impact on the survival of Bale Mangina, but it also brings challenges in the form of cultural commercialization. Therefore, policies that support sustainable community-based tourism are necessary, where cultural conservation is closely linked to enhancing people's welfare.

From the perspective of social adaptation, the modernization of traditional homes must be carried out with consideration for the principles of sustainability, including the use of materials that support both energy efficiency and thermal comfort. By combining cultural conservation approaches, circular economy principles, and social adaptation strategies, Bale Mangina can continue to be a low-carbon and competitive traditional residential model within the context of sustainable development.

4.5. Implications for the Implementation of Sustainable Architecture

Architectural sustainability has become a key agenda item in the design of modern buildings, particularly in efforts to mitigate climate change and reduce the carbon footprint of construction. Bale Mangina

as a traditional residential model that has survived for centuries, demonstrates how the principles of low-carbon architecture can be effectively implemented by utilizing local materials, passive design strategies, and community-based resource management systems. The implications of Bale Mangina's sustainability for low-carbon architecture could be the cornerstone for future building design approaches that are more adaptive to global environmental challenges.

4.5.1. Vernacular Architecture Models in the Concept of Low-Carbon Architecture

Vernacular architecture plays a crucial role in the development of low-carbon architecture due to its adaptive nature in response to the environment and local resources [18]. Bale Mangina is a tangible example of a building system that optimizes resource efficiency, utilizing key materials such as bamboo, timber, and reeds, which are sourced locally with a significantly lower carbon footprint compared to modern materials like concrete and steel. A Life Cycle Assessment (LCA) study conducted on local materials showed that bamboo has a 60% lower carbon footprint than steel, while reed roofs have higher thermal insulation capabilities than zinc or concrete roofs [31].

The implications of the material systems in Bale Mangina for low-carbon architecture can be applied in the development of modern buildings by integrating renewable and long-lasting natural materials. For example, *engineered bamboo* technology can be a structural alternative to replace concrete in lightweight building construction, while roofing systems based on natural materials such as reeds can be adapted to improve thermal efficiency without the need for artificial cooling.

In the context of urban building design, inspiration from Bale Mangina can also be used to improve green building approaches, especially in sustainability certifications such as LEED (*Leadership in Energy and Environmental Design*) and *Greenship* in Indonesia. Vernacular-based building design can reduce operational energy requirements and increase the resilience of buildings to climate change, as seen in several eco-village projects in Southeast Asia that incorporate traditional architectural principles with green technology systems [4].

4.5.2. Integration of Passive Design Strategies for Energy Efficiency

One of Bale Mangina's advantages in supporting low-carbon architecture is the implementation of passive design strategies that can reduce building energy consumption. By using a natural ventilation system based on bamboo-woven walls and reed roofs, Bale Mangina can maintain a cool indoor temperature

without relying on artificial cooling systems. Temperature measurements show that the temperature inside the Bale Mangina ranges from 23–28°C, while the outdoor temperature can reach 30°C or more. This demonstrates that the passive design applied is capable of reducing energy requirements by up to 50% compared to modern houses made of concrete [32].

The application of this strategy to modern building design implies that the concept of adaptive thermal comfort can be integrated into future architectural projects, particularly in tropical regions. The use of walls that allow for natural air exchange, combined with the use of organic roofs featuring high thermal insulation, can reduce cooling costs by up to 30% in office buildings or settlements with a *green living concept* [33].

In addition, the use of green roofs and high-permeability materials, as applied to Bale Mangina, can be developed to create a more environmentally friendly built environment. This concept has been implemented in several *Net Zero Energy Building* (NZEB) projects, focusing on reducing operational energy consumption through the use of natural material-based designs that facilitate optimal air circulation [34].

4.5.3. Circular Economy and Community-Based Resource Management

Bale Mangina's sustainability is also closely linked to a community-based resource management system, which enables the use of building materials in a closed-loop cycle. The concept of *circular economy* in architecture refers to the principle of using materials that can be recycled or returned to nature without generating excess waste [35]. In Bale Mangina, materials such as reeds, bamboo, and wood can undergo a cycle of reuse, where used reeds are used as agricultural mulch. In contrast, old wood is utilized as biomass fuel or secondary construction materials.

The implication of this system in sustainable architecture is that the concept of *biodegradable materials* can be a solution in designing future buildings that are more environmentally friendly. In modern housing projects, this system can be implemented by:

1. Utilization of renewable natural materials, such as engineered bamboo or natural fibers, for wall and insulation panel applications.
2. Community-based waste management, with the concept of recycling building materials, reduces the consumption of new resources.
3. The modular design is cradle-to-cradle-based, allowing materials to be reused in sustainable building systems.

A study by Li, et al. [36] demonstrates that buildings implementing a circular economy system can reduce their carbon footprint by up to 40% compared to conventional buildings. By adapting the practices implemented in Bale Mangina, the modern construction sector can develop a more sustainable and low-carbon community-based material system.

4.5.4. Policy Directions and Implementation in Sustainable Development

The implications of this study for sustainable architecture policy are that traditional architecture-based approaches can be a more effective strategy for mitigating climate change compared to high-tech approaches, which often have more significant environmental impacts [37]. Some policy recommendations that can be developed based on the Bale Mangina principles include:

1. Integration of vernacular-based design into green building regulations by adopting the principles of passive design and utilizing natural materials in national construction standards.
2. Incentives for the use of low-carbon materials, such as bamboo and reeds, in sustainable housing projects that can be combined with modern technology.
3. Community empowerment in local resource management to ensure that building materials can be obtained sustainably and support the local economy.

In addition, with the increasing global awareness of green architecture, Bale Mangina-based approaches can also be applied in the context of urban development by developing green settlement zones that incorporate local culture, thereby allowing for the integration of traditional design and renewable energy technologies [38].

Bale Mangina, as a traditional architectural model, demonstrates that the principles of low-carbon architecture can be applied through the use of natural materials, passive design, and community-based resource management. The implications of this study for sustainable architecture in the future suggest that by adapting traditional practices to modern construction systems, we can reduce operational carbon emissions, enhance energy efficiency, and support a circular economy in the building industry.

This approach is becoming particularly relevant in the face of climate change challenges, where vernacular architecture, such as Bale Mangina, can serve as an essential reference in building sustainable settlements that are more adaptive and environmentally friendly. Based on the explanation above, a table can be created to illustrate the relationships between existing and proposed passive design strategies and sustainability and low-carbon construction indicators as follows:

Table 1. Passive Design Strategies and Low Carbon Indicators in Bale Mangina (Source: Researches analysis, 2025)

Passive Design Strategy	Application in Bale Mangina	Low-Carbon/ Sustainability Benefits
Building Orientation	Houses oriented along the north-south axis	- Enhances natural lighting and ventilation, improves indoor comfort - Reduces energy demand for heating, cooling, and lighting
Natural Ventilation	Saddle-shaped roof and woven bamboo walls promote airflow	- Improves indoor air quality, reduces reliance on mechanical systems - Cuts electricity use and operational carbon emissions
Thermal Mass	Use of thick thatched roof and ground flooring for higher thermal insulation	- Stabilizes indoor temperatures, reduces HVAC demand - Minimizes energy peaks and associated emissions
Solar Shading (e.g. louvers, overhangs)	Wide eaves and overhangs help provide shading and reduce overheating	- Prevents overheating, reduces cooling load - Reduces demand for air conditioning
Use of Local & Natural Materials	Locally sourced bamboo and reeds	- Lowers embodied energy and emissions - supports the principle of a circular economy, where materials are utilized in a sustainable cycle, generating minimal waste

4.6. Recommendations to Stakeholders

The roles of the government, community, academics, and architects in supporting low-carbon development are as follows:

- Governments should adopt vernacular principles in their green building policies and incentivize sustainable practices.
- Communities can help preserve traditional architecture, promote the use of local materials, and develop ecotourism-based economies.
- Academics should explore eco-friendly technologies and assess traditional designs using Life Cycle Assessment.
- Architects must integrate passive design and natural materials, creating hybrid solutions that strike a balance between tradition and sustainability.

4.7. Suggestions for Further Research

While this study offers valuable insights into Bale Mangina's role in low-carbon architecture, future research could explore its energy efficiency through simulations, test the carbon impact of different local materials, and examine the integration of technologies like solar panels without altering its design. Research could also focus on circular waste management, scaling the model to urban areas, and assessing policy incentives. A multidisciplinary approach is key to expanding the application of traditional, sustainable architecture to address global environmental challenges.

5. Conclusion

This study has provided a detailed assessment of the Bale Mangina as an exemplar of low-carbon, sustainable vernacular architecture in Senaru, North Lombok. By combining field observations, interviews, and literature analysis, the research demonstrates how the strategic use of local materials such as bamboo and reeds, alongside passive design features like natural ventilation and thermal insulation, significantly reduces both energy consumption and carbon emissions. These traditional design strategies maintain comfortable indoor temperatures without the need for mechanical systems, offering clear evidence of environmental efficiency.

Moreover, the study highlights that sustainability in this context extends beyond technical performance; it is deeply embedded within the cultural and social systems of the community. Practices such as gotong royong (mutual cooperation) reinforce resilience, cultural continuity, and shared responsibility, thereby contributing to the long-term sustainability of the built environment.

The insights gained from the Bale Mangina suggest that integrating vernacular knowledge and passive design strategies into contemporary architectural practice can play a key role in advancing global sustainability goals. Future research should explore how these principles can be adapted to urban contexts and scaled through the use of modern materials and technologies, ensuring that architectural innovation remains sensitive to both cultural heritage and environmental imperatives.

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