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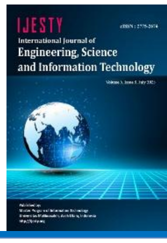

Composite Material Engineering Analysis Based on Circular Economy for the Conservation of Interior Ornaments and Traditional Balinese Architecture

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Abstract

This study examines the engineering and application of sustainable composite materials as an alternative to traditional Balinese architectural ornaments through a comparative analysis of four material types: fiberglass, precast concrete, glass fiber-reinforced cement (GRC), and artificial sandstone. The scarcity of natural materials, growing ecological pressures, and the demand for economic efficiency and ease of production have driven the exploration of engineered materials that can represent Balinese architecture's aesthetic, symbolic, and spiritual values. The research employs a descriptive-qualitative methodology involving field observations, in-depth interviews with local artisans, and an analysis of each material's technical and cultural characteristics. Fiberglass and GRC stand out for their form flexibility and suitability for mass production, while precast concrete offers superior structural durability and long-term maintenance efficiency. Meanwhile, community-driven innovations in artificial sandstone exhibit strong potential for preserving traditional values while addressing contemporary sustainability challenges. The findings suggest that no single material emerges as universally superior; therefore, material selection should be context-dependent, considering both economic feasibility and cultural compatibility. The study concludes that integrating material innovation into traditional architecture must be grounded in circular economy principles, active community participation, and a deep understanding of vernacular values. These insights are expected to serve as a strategic reference for material selection in preserving Balinese cultural heritage while supporting the contextual and competitive development of the local creative industry within the Southeast Asian region.

Keywords: *Balinese Architecture, Creative Economy, Building Material Innovation, Sustainability, Composite Materials.*

1. Introduction

Traditional Balinese Architecture (TBA) represents a distinctive cultural heritage deeply rooted in profound philosophical values. Its rich spiritual and aesthetic dimensions are manifested through various architectural elements, particularly in the intricately carved ornaments that serve as visual and symbolic identifiers. One of the primary materials traditionally used for these ornaments is *padas* stone, a fine-textured volcanic stone easily carved and visually harmonizes with Bali's tropical environment. However, as development intensifies and natural resources are increasingly exploited, the availability of natural *padas* stone has significantly declined. Unregulated mining activities and government restrictions on illegal quarrying have limited access to this essential material [1]. Consequently, preserving Balinese cultural identity through architecture faces critical challenges unless alternative materials can uphold TBA's philosophical and aesthetic values [2].
In this context, advances in material technology offer promising opportunities for developing sustainable composite building materials that can substitute traditional resources [3]. Fiberglass, precast concrete, Glass Fiber Reinforced Cement (GRC), and artificial *padas* stone have been increasingly explored for architectural ornamentation [4]. Each of these materials presents unique advantages, ranging from structural strength and ease of production to visual resemblance with natural stone. Fiberglass, for instance, is valued for its design flexibility and high weather resistance. GRC offers structural durability and is well-suited for replicating intricate ornamentation through molding. Precast concrete excels in mass production efficiency and long-term durability. At the same time, artificial *padas* stone,

produced using local materials such as cement, sand, and pozzolan, preserves natural textures and appearances while being more environmentally and economically viable. Preliminary studies have shown that these materials can replicate the properties of natural *padas* stone at a lower cost and with reduced environmental impact. The demand for traditional architectural ornaments has increased in response to the growing popularity of Balinese-style tourism and residential developments [5]. This is reinforced by Regional Regulation No. 5 of 2005, which mandates incorporating Balinese architectural elements in building design. As hotels, villas, and public facilities increasingly adopt TBA features to enhance cultural appeal [2], natural *padas*, limited stone availability, and rising costs have made their use less feasible. This underscores the urgent need for research into alternative materials that can bridge the gap between cultural preservation and modern development requirements.

Although fiberglass has been widely applied in modern ornament production, its role in the context of TBA has not been thoroughly examined. Issues such as its petroleum-based resin content, challenges to recyclability, and potential microplastic pollution raise environmental concerns [6]. Therefore, the selection of alternative materials must consider long-term sustainability, including production processes, waste generation, and recyclability. Precast concrete and GRC have produced precise and durable ornaments suited to tropical climates. Research indicates that GRC can effectively replicate traditional carvings while offering reduced weight compared to natural stone [7], facilitating easier installation and reducing structural loads. However, cultural acceptance and alignment with local values remain significant challenges. From a socio-cultural perspective, adopting modern materials in TBA extends beyond technical considerations. The transmission of values, symbols, and architectural meanings is deeply connected to traditional material usage.

Many traditional artisans (*undagi*) have expressed concerns about using non-traditional materials that may not align with spiritual values and customary principles, such as those in *the Asta Kosala-Kosali tradition* [8]. Therefore, innovation must be pursued through participatory approaches that actively engage local communities. Meanwhile, studies on artificial *padas* stones have shown promising results regarding compressive strength, color resemblance, and cost-efficiency [9]. Utilizing locally available materials such as volcanic ash and pozzolan enhances environmental friendliness and ensures economic accessibility. Nonetheless, long-term factors such as resistance to humidity, moss growth, and weathering require further testing before artificial *padas* stone can be standardized for mass production of TBA ornaments. The urgency of this research is further underscored by the lack of comprehensive studies that systematically and holistically compare these four materials, especially within the context of TBA ornamentation. Most existing studies focus on the technical aspects of a single material or overlook the socio-cultural dimensions of their application. Yet, the success of material substitution largely depends on community acceptance, aesthetic value, and compatibility with local philosophical and cultural frameworks. [10].

This study compares four composite materials—fiberglass, precast concrete, GRC, and artificial *padas* stone within Balinese architectural ornaments. The evaluation encompasses technical aspects such as strength, durability, and production feasibility alongside aesthetic compatibility, cultural value, and environmental impact considerations. A descriptive-qualitative research approach involves conducting field observations, in-depth interviews with artisans, and analyzing physical materials. To date, no comprehensive study has holistically compared these four materials in the context of TBA, integrating technical, cultural, and sustainability perspectives. By adopting a multidimensional approach, this research aims to make a meaningful contribution to the preservation of TBA by developing contextually appropriate material innovations. Moreover, the study aligns with the broader agenda of culturally rooted creative economies, empowering local artisans and offering policy-relevant insights into architectural conservation. As such, the research lies at the intersection of building material technology, cultural heritage preservation, and environmental sustainability, providing technical contributions and a practical pathway for safeguarding Bali's architectural legacy amid the demands of modernity.

2. Literature Review

Material selection in traditional architecture is not merely a technical concern; it is deeply intertwined with the expression of cultural and spiritual values. Within the Traditional Balinese Architecture (TBA) context, ornaments serve more than just aesthetic purposes—they embody philosophical concepts, such as *Tri Hita Karana*, which emphasizes harmony between humans, nature, and the divine [6]. Materials such as *padas* stone and traditional bricks have long been preferred due to their workability, distinctive visual appeal, and intrinsic connection to the sacredness and the earth. However, the increasing scarcity of *padas* stone, driven by overexploitation and mining restrictions, has necessitated the exploration of alternative materials that can preserve cultural significance and aesthetic quality. Advances in material science have introduced several composite alternatives, including fiberglass, precast concrete, Glass Fiber Reinforced Cement (GRC), and artificial *padas* stone. Each offers distinct advantages: fiberglass is praised for its design flexibility and suitability for mass production; precast concrete is known for its strength and low maintenance; GRC allows for high-precision carving; and artificial *padas* stone offers strong visual resemblance and cultural acceptance.

International studies highlight that integrating technology in vernacular architecture can enhance cultural preservation efforts, provided that local values and ecological sustainability are upheld [11]. Within the framework of sustainable architecture, material selection must extend beyond considerations of durability and aesthetics to incorporate a comprehensive lifecycle analysis. Life Cycle Assessment (LCA) has become a widely accepted method for evaluating the environmental impacts of materials, encompassing the entire life cycle, from extraction to end-of-life stages [12]. According to Asif (2022), materials such as fiberglass impose significant ecological burdens due to their non-biodegradable nature and incompatibility with the principles of a circular economy. In contrast, locally sourced materials like artificial *padas* stone from pozzolanic waste or volcanic ash support closed-loop production systems and exhibit lower carbon footprints. This aligns with findings by Acwin Dwijendra, who emphasizes the importance of circular economy-based architectural design for reintegrating materials into sustainable production cycles [3].

The socio-cultural dimension is equally critical to successfully adopting new materials in traditional architecture. Balinese artisans and cultural leaders consistently stress that a material's spiritual suitability—possessing tasks (sacred energy or spiritual resonance)—is a decisive factor for acceptance. The community often rejects materials that lack tasks, even if their form and appearance closely mimic traditional counterparts [13]. This underscores the importance of community acceptance in material innovation, as evidenced in vernacular architectural preservation studies across Southeast Asia. [14].

Generally, material selection in the context of TBA must simultaneously consider technical, aesthetic, ecological, and socio-cultural dimensions. However, previous studies have tended to be fragmented and sectoral—for instance, focusing solely on the compressive strength of GRC, the tropical climate resilience of fiberglass, or the cost-efficiency of precast concrete—without conducting a comprehensive analysis of all four materials within the complex context of TBA. Material decisions based on a single criterion risk failing to address the cultural preservation challenges posed by sustainable development demands. Hence, a multidimensional approach is essential—one that incorporates technical and economic efficiency, environmental sustainability, and cultural legitimacy. Integrating circular economy principles into material production and use and a deep understanding of local socio-cultural values can lead to more relevant and sustainable strategies. Within the creative economy and green architecture framework, engineering composite materials for TBA can strategically preserve Balinese cultural heritage while enhancing its competitiveness as part of Southeast Asia's dynamic vernacular architecture landscape.

3. Methods

This study employs a multidimensional, qualitative, descriptive approach to explore and compare the characteristics of four types of composite materials—fiberglass, precast concrete, Glass Fiber Reinforced Cement (GRC), and artificial padas stone — in their application to interior ornamentation and Traditional Balinese Architecture (TBA). This approach enabled a holistic understanding of material-related phenomena, encompassing technical, aesthetic, sustainability, and cultural dimensions. These four dimensions include: (1) technical performance (durability, strength, modularity); (2) aesthetic quality (visual resemblance, ornamental precision); (3) material sustainability (carbon footprint, recyclability potential, circularity score); and (4) cultural appropriateness (symbolic value, community acceptance, and harmony with *Tri Hita Karana* and *Asta Kosala-Kosali* principles). Data were collected through three primary methods: participatory field observation, semi-structured interviews, and systematic literature review. Field observations were conducted in Gianyar, Badung, Bangli, and Denpasar regencies, focusing on producing and applying ornaments made from composite materials. Interviews were conducted with 18 key informants, including traditional artisans (*undagi*), conservation architects, academic experts, cultural figures, and local cultural officers, using interview guidelines grounded in circular economy principles and community-based conservation approaches. The literature review included sources from books, Scopus- and SINTA-indexed journals, publications on tropical architecture, regional policy documents, and previous research studies. Data analysis was conducted using thematic categorization and cross-case comparisons between locations and material types. The validity of the research was maintained through triangulation of sources, methods, and member checking [15]. The researchers also developed a material evaluation matrix based on circularity scores, life cycle assessment (LCA), and indicators of community acceptance, which served as both an analytical tool and a basis for policy recommendations. This study thus contributes an adaptive evaluative framework for conserving vernacular architecture and developing culturally rooted sustainable architecture.

4. Result and Discussion

4.1. Empirical Evaluation of Composite Materials in Balinese Architectural Ornaments.

Recent advancements in material technology over the past decades have significantly expanded the range of building materials available, including those applicable to preserving traditional architecture. In the traditional Balinese architecture (TBA) context, material innovation has become increasingly urgent, particularly due to the diminishing availability of natural padas stone, which results from excessive exploitation and environmental regulations. Ornaments in TBA serve an aesthetic purpose and carry deep philosophical meaning, one of which is the symbolic representation of *Tri Hita Karana*, the Balinese principle of harmony among humans, nature, and the divine [9]. Consequently, any attempt to replace traditional materials must be grounded in a multidimensional evaluation considering technical performance, aesthetic quality, sustainability, and cultural acceptance. One of the most widely adopted alternative materials is fiberglass. This material comprises synthetic resin, catalyst, fiberglass mat, and additives, including color pigments and silicone oil [7]. Fiberglass is well known for its lightweight nature, easy molding into complex shapes, and rapid production time.[16]. These advantages make it suitable for significant ornamental elements in hard-to-reach architectural locations. Figures 1, 2, and 3 illustrate the application of fiberglass-based ornaments in buildings located in the regencies of Gianyar, Badung, and Tabanan. However, from an ecological standpoint, fiberglass has limitations due to its non-biodegradable nature and its potential to cause environmental pollution. Therefore, using fiberglass must be accompanied by appropriate recycling systems or waste processing technologies to ensure its alignment with sustainability principles.

Fig 1. Use of Fiberglass Material on the UC Silver Building in Gianyar, Bali.
Source: Author

Fig 2. Use of Fiberglass Material on the Garuda Wisnu Serasi Open Stage at Bung Karno Park, Tabanan.
Source: Author

Fig 3. Use of Fiberglass Material on the Badung Regency Government Center Building.
Source: Author

In addition to fiberglass, precast concrete has emerged as a rapidly developing alternative material. Precast concrete is a mixture of cement, sand, water, and steel reinforcement, molded to resemble traditional architectural elements [17]. Local communities in Bali first developed this material in the 1980s to respond to the rising cost of high-quality timber. It replicated various TBA ornaments such as *saka* (columns), pintu Bali (Balinese gateways), and other carved elements. Precast concrete offers high durability, resistance to decay, and excellent performance under extreme weather conditions. Its modular production process allows for greater efficiency in both manufacturing and installation. Figure 4 illustrates the production process of precast concrete ornaments and their application in TBA structures. Moreover, this material supports modular reuse systems, where architectural elements can be dismantled and reused, aligning well with the principles of a circular economy. The advantages of precast concrete lie in its strength, production efficiency, and widespread social acceptance. Traditional aesthetic values can be preserved by carefully applying visual finishing techniques. This balance between innovation and tradition reinforces its viability as a culturally sensitive and environmentally sustainable building material.

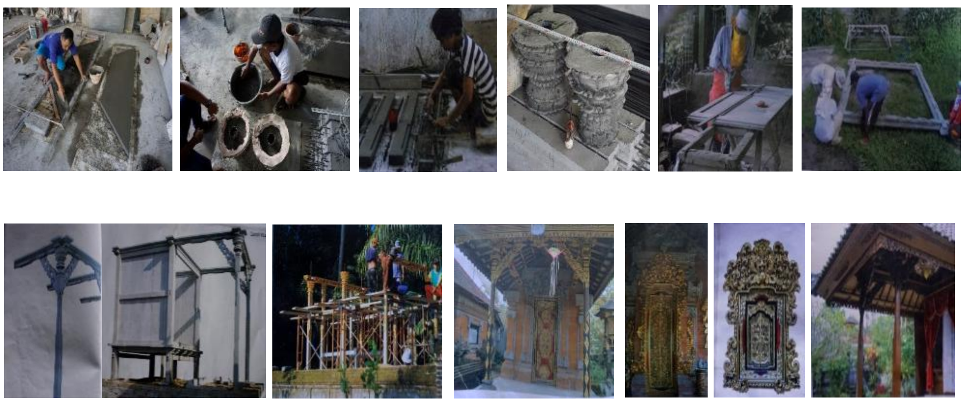

Fig 4. Use of Precast Concrete Ornaments in TBA Structures
Source: Author

Another notable innovation is artificial *padas* stone, which has emerged as a local solution to the scarcity of natural *padas* stone. This material is produced from *padas* stone waste mixed with cement and water, then molded using wooden formwork boards and carved according to design specifications. The production process is illustrated in Figure 5, which shows the stages from mixing and molding to the formation of the ornament. Artificial *padas* stone closely resembles natural stone in appearance and texture. They are lighter, more cost-effective, and demonstrate superior durability. Its use eliminates the need for new quarrying activities, aligning with the principles of the circular economy [18]. This innovation has been pioneered by small-scale industrial groups in Bali, particularly in the Gianyar, Tabanan, and Badung regencies, and is integrated into community-based creative economy practices. Artificial *stone has* produced various ornaments, including statues, wall reliefs, interior decorative panels, and *karang boma* elements. Depending on the design's complexity, the typical production time ranges from three to five days. The key advantages of artificial *padas* stone lie in its visual similarity to natural stone, affordability, and high community acceptance, as it continues to be regarded as spiritually meaningful. This innovation empowers local artisans, preserves traditional knowledge, and responds to ecological challenges. Repurposing leftover *padas* stone fragments also bridges cultural resistance to modern materials, reinforcing environmental and cultural sustainability.

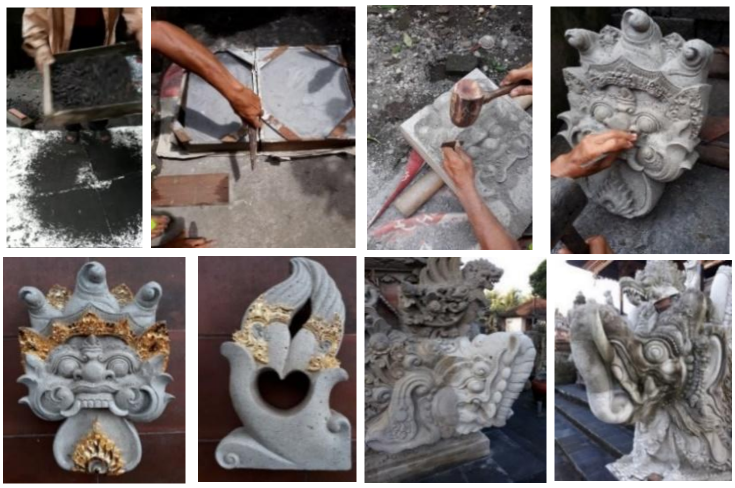

Fig 5. Main Stages in the Production of Artificial *Padas* Stone
Source: Author

Another material of significant interest is Glass Fiber Reinforced Cement (GRC), a composite of cement and glass fibers that produces a lightweight, thin, yet mechanically strong material [19]. Figure 6 illustrates the application of GRC ornaments on large-scale structures such as Ngurah Rai International Airport and Badung Market in Denpasar. GRC excels in form precision and design flexibility, making it ideal for large-scale ornaments with intricate carving details.

A study by Nadia Nassif et al. (2024) highlights that GRC possesses a high strength-to-weight ratio and resistance to dynamic loads, making it especially suitable for external façades [6]. However, the sustainability of GRC remains a challenge, as the chemical composition of glass fibers makes recycling difficult. Several solutions have been developed, including using bio-resins and closed-loop recycling systems, which enable GRC waste to be reintegrated into new production processes.

Fig 6. Use of Precast Concrete Ornaments at Ngurah Rai International Airport
Source: Author

Artificial *padas* stone is the most ideal candidate among the four evaluated materials. This material meets all assessment criteria: it is technically durable, has low carbon emissions, is culturally accepted, and is socially beneficial. It also carries spiritual legitimacy, as it is derived from earthen elements, aligning with the philosophical values of *Asta Kosala-Kosali*. In addition, its lighter weight contributes to reduced production and transportation costs. A circular economy-based approach to material engineering is critical in traditional architecture. Materials must be evaluated for their structural performance, life cycle, ecological impact, and symbolic meaning within the local cultural framework. Table 1 (if presented) can provide a comparative overview of the four materials across four primary dimensions: technical, aesthetic, environmental sustainability, and cultural alignment. Recent studies indicate that while fiberglass and GRC offer high design flexibility and mechanical strength, their circularity and community acceptance limitations make them less suitable for conserving TBA. In contrast, precast concrete and artificial *padas* stone present more balanced solutions, simultaneously addressing cultural preservation and ecological sustainability.

These findings underscore the importance of adopting a multidimensional approach in material selection for TBA. Material choice is not merely a matter of efficiency or visual appeal—it must also address sustainability and cultural rootedness issues. Artificial *padas* stone emerges not only as a technical solution but also as a symbol of locally driven innovation, responding to contemporary challenges. It represents a synthesis of heritage and technology, sustainability and spirituality, preservation and adaptation. Therefore, the continued development of material engineering grounded in local values and circular economy principles is essential for ensuring the long-term sustainability of Traditional Balinese Architecture.

4.2. Technical and Strategic Evaluation of Composite Materials in the Context of Traditional Balinese Architectural Ornaments

To preserve Traditional Balinese Architecture (TBA), the selection of substitute materials for architectural ornaments must be approached through a multidimensional framework that considers technical performance, sustainability, aesthetics, cultural legitimacy, and user preferences. This evaluation requires a synthesis of quantitative analysis based on material performance and a qualitative understanding of social and cultural stakeholder perceptions. The initial stage involved mapping the technical attributes of each composite material, including fiberglass, precast concrete, Glass Fiber Reinforced Cement (GRC), and artificial *padas* stone. This evaluation was structured around nine key indicators: material weight, form flexibility, visual resemblance to natural *padas* stone, weather resistance, environmental friendliness, production cost, compressive strength, ease of mass production, and acceptance within local cultural contexts.

Table 1. Performance Comparison of Materials: Fiberglass, Precast Concrete, GRC, and Artificial *Padas Stone*
Source: Author's Analysis

Aspect	Fiberglass	Precast Concrete	GRC (Glass Fiber Reinforced Cement)	Artificial *padas* Stone
Material Weight	Light	Heavy	Medium	Medium
Form Flexibility	Very Flexible	Slightly Flexible	Flexible	Moderately Flexible
Aesthetic Similarity to *Padas* Stone	Moderate	High	High	High
Weather Resistance	High	High	High	Moderate
Environmental Friendliness	Low	Moderate	Moderate	High

The analysis results indicate that fiberglass excels in lightweight properties and very high form flexibility, making it the preferred choice for complex ornamentation projects requiring rapid production. However, this material ranks low in sustainability due to its composition of non-biodegradable synthetic resins [16]. In contrast, precast concrete offers high structural strength, strong weather resistance, and a close aesthetic resemblance to traditional *padas* stone ornaments. Although heavy and only slightly flexible, it is highly efficient for mass production and aligns with the principles of a circular economy. Meanwhile, Glass Fiber Reinforced Cement (GRC) occupies an intermediate position, offering advantages in carving precision and moderate flexibility [20] . Its application in large-scale projects such as Ngurah Rai International Airport and Badung Market emphasizes its strengths in precision and form adaptability. However, GRC also faces sustainability challenges due to its reliance on cement and synthetic fibers, which are difficult to recycle.

Lastly, artificial *padas* stone is the most balanced material across all dimensions. It is highly sustainable and produced from *padas* stone waste and local pozzolanic materials. It is recyclable and enjoys spiritual legitimacy and cultural acceptance among local communities. Each material presents its strengths and weaknesses, depending on the context of use and project priorities. Furthermore, Table 2 presents a strategic SWOT analysis of each material. Fiberglass shows strong opportunities in mass production and installation efficiency but faces threats from cultural resistance and a lack of symbolic value. While strong and efficient, precast concrete is often perceived as lacking aesthetic refinement for prestigious projects. GRC is well-suited for prefabricated elements with high detail requirements but poses technical and cost-related constraints. Artificial *padas* stone, on the other hand, excels in visual harmony and cultural acceptance but still requires further standardization and long-term durability testing.

Table 2. Strategic Comparison of Materials: Fiberglass, Precast Concrete, GRC, and Artificial *Padas* Stone.

Material	Strengths	Weaknesses	Opportunities	Threats
Fiberglass	Lightweight, flexible shape	Non-biodegradable, synthetic resin	Mass production, fast installation	Cultural resistance lacks symbolic value
Precast Concrete	Durable, strong, cost-effective	Heavy, visually rigid	Widely available, adaptable to local projects	Aesthetic rejection in high-end markets
GRC	High precision, suitable for detailed ornament	It can be brittle, expensive	Ideal for prefabricated panels	Technically demanding, costlier
Artificial *Padas* Stone	High visual similarity, culturally accepted	It still requires testing for long-term durability	It supports the local economy and is eco-friendly	Not yet standardized, susceptible to climate

Source: Author's Analysis

Meanwhile, Figure 7 presents the distribution of material preferences across stakeholder groups. The data indicate that 70% of architects and 75% of community members selected artificial *padas* stone as their primary material, citing its visual resemblance to natural stone and its sustainability value. In contrast, precast concrete was favored by 60% of architects and 65% of regulatory authorities, primarily due to its efficiency in production and installation. From the client's perspective, 65% preferred artificial *padas* stone, while 55% selected precast concrete. Fiberglass and GRC were more commonly favored in commercial or modern architectural projects, where high precision and fast installation are prioritized.

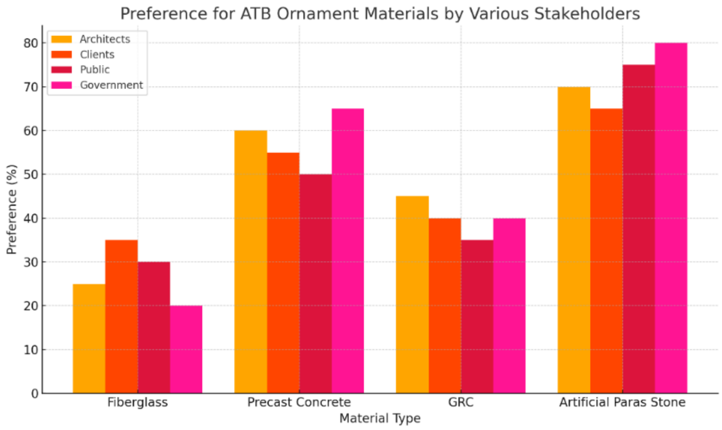

Fig 7. Material Preferences by Stakeholder Group
Source: Author's Analysis

These findings are reinforced by interview results, which reveal that artificial padas stone and precast concrete are still perceived as containing "earth elements"—an essential component of Balinese spirituality, aligned with the principles of Tri Hita Karana and the values of Asta Kosala-Kosali. Materials derived from the earth and processed through traditional methods are believed to possess taksu, or spiritual essence, which is thought to imbue buildings with symbolic power. In contrast, fiberglass is viewed as overly artificial, modern, and lacking taksu, making it less acceptable for sacred structures or traditional homes. Therefore, a participatory approach to material selection must ensure innovation remains grounded in cultural roots. This research emphasizes that innovation processes should not be based solely on technical performance or production efficiency but must also reflect ecological and social responsibility.

From the collective findings, it can be concluded that artificial *padas* stone and precast concrete are the two most strategic materials for future development in TBA conservation. Fiberglass and GRC remain relevant in specific project contexts that demand high design flexibility or rapid execution, provided their use is selective and accompanied by environmental mitigation [21]. Thus, the multidimensional evaluation approach, which integrates technical, sustainability, aesthetic, and cultural legitimacy aspects, as illustrated in Tables 1 and 2, Figure 1, and Figures 1–7, offers both a scientific and practical foundation for informed decision-making in the preservation and development of Traditional Balinese Architecture. In this context, composite material innovation is not merely a matter of technical substitution but a manifestation of value transformation that ensures continuity between cultural heritage and contemporary demands.

4.3. Integrating Circular Economy and Strategic Material Evaluation

As sustainability practices in design and construction become increasingly urgent, applying circular economy (CE) principles, such as architectural ornamentation, is crucial at both the building scale and the micro level [22]. In the traditional Balinese architecture (TBA), ornaments carry significant cultural and spiritual meaning. Therefore, material selection for ornamentation must align with local values and circularity principles to address current ecological challenges while preserving cultural heritage. Materials such as artificial *padas* stone and precast concrete occupy strategic positions within the circular economy framework, as they can be produced from local resources and construction waste. They support modular design that allows for disassembly and reuse. For instance, incorporating natural pozzolans, such as rice husk ash and volcanic ash, into concrete reduces carbon emissions from cement and enhances the durability and lifespan of architectural ornaments. Additionally, using locally sourced materials shortens supply chains and reduces logistical carbon footprints.
In contrast, fiberglass and GRC show limitations in achieving circularity. Fiberglass poses significant recycling challenges and contributes to microplastic pollution, while GRC—comprising cement and synthetic fibers—has yet to fully support closed-loop recycling systems. Innovations such as biodegradable resin formulations and integrated recycling systems must be further developed to ensure these materials meet future sustainability standards. Table 3 presents the circularity scores of the four TBA ornament materials, evaluated across four key aspects: use of local materials, recyclability, production emissions, and potential for modular reuse. Artificial *padas* stone achieved the highest score (17/20), followed by precast concrete (15), GRC (12), and fiberglass (7). These findings are visually confirmed in Figure 8, which illustrates the relative circularity performance of each material..

Table 3. Circular Economy Score of ATB Ornament Materials (Skala 1–5)

Aspect / Material	Fiberglass	Precast Concrete	GRC	Artificial *Padas* Stone
Use of Local Materials	1	4	3	5
Ease of Recycling	1	3	2	4
Low Production Emissions	2	3	3	4
Potential for Reuse / Modular Design	3	5	4	4
Total Skor Circularity	7	15	12	17

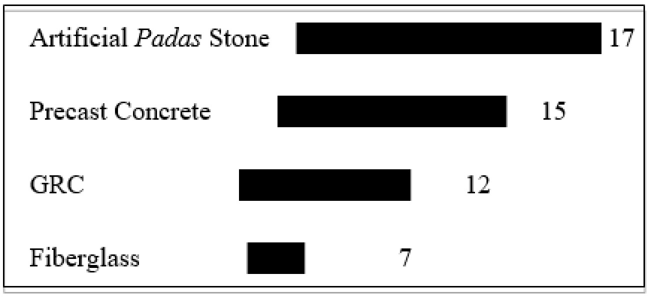

Fig 8. Skor Circular Economy per Material (Skala 1–20)

Comparing long-term material impacts becomes crucial from a Material Lifecycle Assessment (LCA) perspective. The evaluation includes factors such as production energy consumption, service lifespan, recyclability, carbon emissions, and end-of-life waste, as summarized in Table 4. The results show that artificial *padas* stone possesses the highest sustainability profile, requiring low production energy, offering high recyclability, and generating minimal waste, making it an ideal material for application in Traditional Balinese Architecture (TBA). In contrast, fiberglass exhibits high carbon emissions, limited recycling potential, and generates non-biodegradable waste, making it a less optimal choice for sustainable architectural practices.

Table 4. Lifecycle Characteristics of Composite Materials

Material	Production Energy	Lifespan	Recyclability	Carbon Emission	End-of-Life Waste
Fiberglass	High	Medium	Low	High	Non-biodegradable
Precast Concrete	Medium	Long	Medium	Medium	Crushed/Reusable
GRC	Medium	Long	Medium	Medium	Limited Recycling
Artificial Padas Stone	Low	Long	High	Low	Minimal Waste

Figure 9 reinforces these findings by illustrating that artificial Padas stone demonstrates the most favorable combination of low carbon emissions and high recyclability. In contrast, fiberglass occupies the lowest end of the spectrum for both indicators.

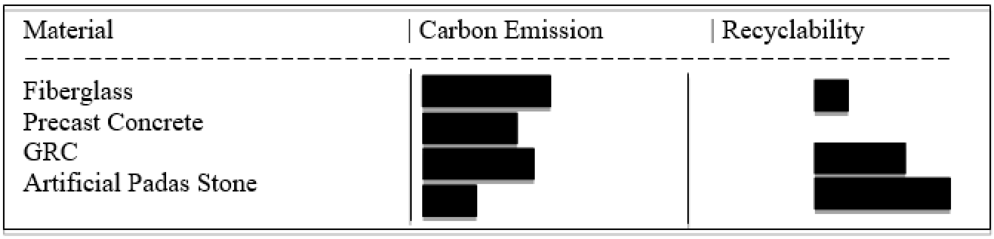

Fig 9. Lifecycle: Carbon Emission & Recyclability

Overall, this discussion confirms that the transition strategy toward a circular economy in TBA ornamentation necessitates material selection based on quantitative and qualitative evaluation. Artificial *padas* stone and precast concrete emerge as ideal solutions due to their compatibility with local contexts and ecological sustainability. While fiberglass and GRC still hold potential for use in projects with specific technical requirements, their success will ultimately depend on material innovation and the development of sustainable lifecycle management systems.

4.4. Integration of Cultural Values and Sustainable Technology in Material Selection for Traditional Balinese Architectural Ornaments: A Theoretical Framework Based on the Circular Economy

The theoretical framework developed in this study integrates four primary domains—culture, technology, sustainability, and architecture—to form a comprehensive multidisciplinary approach for evaluating ornament materials in Traditional Balinese Architecture (TBA). The principles of *Tri Hita Karana* and *Asta Kosala-Kosali* represent the cultural domain, which serves as the philosophical foundation and normative guidelines for traditional design. These principles ensure that any material used is spiritually and culturally aligned within Balinese society's sacred and profane spatial contexts. On the other hand, the technological domain encompasses modern materials such as fiberglass, GRC, precast concrete, and artificial *padas* stone, which introduce new levels of efficiency and durability in ornament production. However, technology is not merely a symbol of modernization—it is an adaptive instrument that must be contextualized to avoid eroding traditional values.

Furthermore, the framework emphasizes sustainability as a central evaluative dimension. Table 5 presents the interrelation between domains, key concepts, and their strategic roles within the framework. Sustainability is positioned as a long-term measure of ecological responsibility through indicators such as recyclability, carbon emissions, and Life Cycle Assessment (LCA). Within this context, artificial *padas* stone achieved the highest circularity score, while fiberglass ranked lowest due to its high emissions and non-biodegradable waste.

Table 5. Key Components of the Theoretical Framework
Source: Author's Analysis

Domain	Key Concepts	Role in Framework
Culture	*Tri Hita Karana*, *Asta Kosala-Kosali*	Ensures material compatibility with traditional spiritual and cultural norms
Technology	Fiberglass, GRC, Concrete, Artificial Stone	Enables alternative material development and modern construction techniques
Sustainability	Recyclability, Carbon Emissions, LCA	Evaluate long-term environmental performance and reuse potential
Architecture	Balinese Traditional Ornamentation	Design context that integrates symbolic and aesthetic function

The intersection of technological feasibility, cultural legitimacy, and environmental accountability is essential for selecting sustainable materials for ATB ornaments. Thus, this framework maps technical performance and integrates cultural legitimacy, technological feasibility, and environmental responsibility in selecting materials for Traditional Balinese Architecture (TBA). This approach is highly relevant for conserving vernacular architecture, which is oriented toward long-term sustainability.

4.5. Socio-Cultural Implications, Ecological Impact, Circular Economy Analysis, and Community Acceptance

In the Traditional Balinese Architecture (TBA) context, material selection cannot be separated from the local culture's symbolic, spiritual, and customary values. Ornaments in TBA are not merely decorative elements; they represent cosmological philosophies such as Tri Hita Karana—the concept of harmony between humans, nature, and the divine—and are governed by the spatial system of Asta Kosala-Kosali, which dictates the orientation and function of space based on levels of sacredness. As a result, any material change, particularly the substitution of natural materials with synthetic alternatives, often sparks cultural debate. Materials such as fiberglass and GRC are frequently considered to lack taksu, the spiritual energy believed to reside in natural elements like stone, wood, and earth. Therefore, material innovation within the context of TBA must be accompanied by a reinterpretation of the symbolic and functional values of the material, as well as active engagement with traditional communities and undagi (traditional architects), to ensure that new materials are socially accepted and retain the essence of tradition.

From an ecological perspective, the shift to artificial materials has implications for carbon footprint, production waste, and resource sustainability. While fiberglass is lightweight and flexible, it has high carbon emissions and is non-biodegradable, contributing to microplastic pollution. GRC, though more structurally sustainable, still contains synthetic components and requires high energy inputs during production. Precast concrete occupies a middle position, offering durability and potential for reuse, although its emissions remain moderate. In contrast, artificial padas stone demonstrates strong ecological performance, as it is produced from local waste materials such as stone dust and pozzolanic ash and processed using low-energy casting techniques that generate minimal waste. This material aligns with comprehensive sustainability principles by combining production efficiency, low emissions, and resource renewal. Within the

Circular Economy (CE) framework, material evaluation can be conducted based on three core principles: eliminating waste and pollution through design, keeping materials in use, and regenerating natural systems. CE is a technical approach and a conceptual framework for assessing how well materials align with long-term sustainability goals. Table 5 and Figure 9 demonstrate that artificial padas stone ranks highest in circularity scores due to its ability to fulfill all three principles. Precast concrete occupies an intermediate position due to its reusability and minimal maintenance requirements. At the same time, fiberglass and GRC lag behind due to their synthetic composition and the limited availability of local recycling systems.

Implementing CE in the TBA context must go beyond production efficiency and waste reduction—it must also consider cultural and social dimensions. Community acceptance has proven to be a crucial variable in successfully adopting material innovations. Innovations rejected by communities due to perceived conflicts with local values are unlikely to be widely implemented, even if they are technically superior. Therefore, the successful transition to a sustainable material system can only be achieved by integrating ecological considerations, circularity principles, cultural values, and social participation. The thematic diagram in Figure 10 illustrates that true sustainability in TBA is achieved when four core pillars—culture, ecology, circularity, and social acceptance—are balanced.

In conclusion, the Circular Economy theory provides a robust foundation for advancing material innovation in TBA without compromising the deep-rooted values of tradition. This approach transforms materials into technically viable solutions with cultural meaning and relevance in addressing today's sustainability challenges. Integrating local values into CE practices strengthens the identity of Traditional Balinese Architecture and opens space for local creative industries to grow within a regenerative and contextually grounded economic ecosystem.

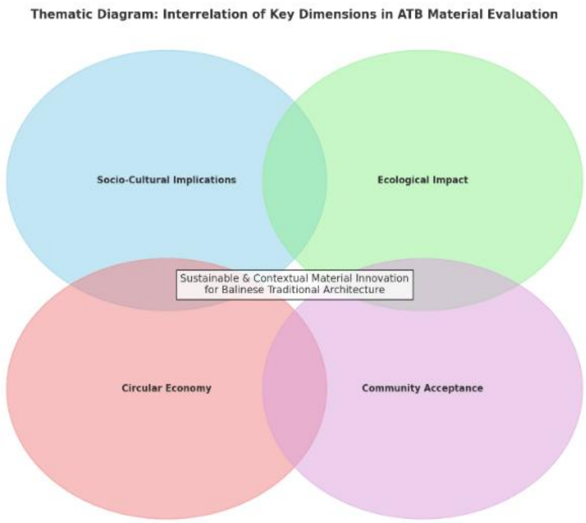

Fig 10. Socio-Cultural Implications, Ecological Impact, Circular Economy Analysis, and Community Acceptance
Source: Author's Analysis

5. Conclusion

This study concludes that selecting composite materials for ornaments in Traditional Balinese Architecture (TBA) must integrate technical performance, environmental sustainability, and cultural legitimacy. Artificial *padas* stone and precast concrete emerge as the ideal options, as they preserve traditional aesthetic values, are sourced from local materials, and support circular economy principles through low emissions and high recyclability. Fiberglass and GRC remain relevant for specific technical needs, particularly in form flexibility and production efficiency; however, both face ecological challenges and cultural resistance. Therefore, the successful adoption of alternative materials depends on participatory strategies that engage architects, artisans, government bodies, and traditional communities in policy development, quality standardization, technical training, and incentive schemes for micro and small enterprises (MSMEs). This approach enables material innovation that is both technologically efficient and adaptable, contextual, inclusive, and socially and culturally sustainable.

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