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From Biomimicry to Climate-Responsive Architecture: Prioritizing Bio-Based and Bio-Inspired Strategies for Sustainable Buildings in Tropical Monsoon Climates

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Abstract

Bio-inspired and bio-based materials are increasingly recognized as powerful enablers of climate-responsive and low-carbon architecture. By learning from natural systems, such as adaptability, self-regulation, and resource efficiency, these materials offer promising solutions to the escalating environmental pressures faced by the built environment. However, their systematic integration into building design remains limited, particularly in tropical monsoon climates. To address this gap, this study applies the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method to identify, prioritize, and map the interdependencies among ten bio-based and bio-inspired strategies for sustainable building design. The results highlight five dominant solutions: living building systems, bio-composite exterior cladding for weather resistance, mycelium-based insulation for humidity control, bio-based natural ventilation and passive cooling, and bio-inspired self-shading systems. The causal analysis reveals three key characteristics: (1) living building systems function as a central integrative nexus, (2) bio-composite cladding acts as a primary driver of durability and climate resilience, and (3) bio-based water filtration and local timber exhibit lower systemic leverage despite their environmental benefits. Theoretically, this study advances biomimetic design research by introducing a causal, system-level framework for understanding interactions among nature-inspired strategies. Practically, it provides architects, engineers, and policymakers with an evidence-based decision-support tool to prioritize climate-adapted, bio-inspired solutions, contributing to the development of resilient and regenerative architecture in rapidly changing climates.



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1. Introduction

The global construction industry stands at the forefront of the climate crisis, contributing significantly to greenhouse gas emissions, resource depletion, and environmental degradation [1,2]. As the built environment accounts for nearly 40% of global energy-related carbon emissions [3,4], there is an urgent need to transition toward more sustainable building practices. Sustainable building design has emerged as a critical response to these

challenges, aiming to minimize environmental impact, enhance energy efficiency, and promote human health and well-being [5–7]. It encompasses not only the use of environmentally responsible technologies and materials but also the thoughtful design of buildings that harmonize with local climates, ecosystems, and communities [8,9]. Addressing sustainability in building design is no longer optional, it is imperative for achieving international climate goals and ensuring resilience in the face of escalating ecological pressures.

Current state-of-the-art building envelope solutions worldwide predominantly rely on standardized materials and physics-based design principles to manage hygro-thermal loads [10]. The integration of bio-based and bio-inspired materials into sustainable building practices offers a promising pathway toward regenerative design. Bio-based materials, derived from renewable biological resources such as agricultural residues, fungi, and timber, present lower embodied carbon and resource intensity compared to conventional building materials [11,12]. Similarly, bio-inspired design draws from natural processes and systems to enhance building performance through passive strategies, adaptability, and resilience [13]. These materials and approaches can improve insulation, moisture management, ventilation, and shading, contributing to healthier indoor environments and reduced reliance on mechanical systems [14–16]. However, despite their potential, the integration of bio-based and bio-inspired strategies into mainstream building design practice remains limited, due in part to technical, regulatory, and knowledge barriers.

In tropical monsoon climates, included Indian subcontinent, Southeast Asia, parts of Africa, and northern Australia, sustainable building design faces challenges from high humidity, heavy rainfall, and seasonal temperature variations, which create favorable conditions for microbial growth on façades, and high levels of solar radiation, lead to a high cooling demand in buildings [17–20]. Buildings must exhibit resilience to moisture damage, facilitate natural ventilation, and achieve thermal comfort with minimal energy consumption [21,22]. Consequently, identifying and implementing appropriate innovative materials and building design strategies are paramount in these regions. While many sustainable building strategies exist globally, a paucity of solutions exists specifically tailored to the demands of tropical monsoon environments. A discernible research gap exists in understanding the efficacy, viability, and impact of bio-based and bio-inspired solutions within this specific climatic context. This study aims to address this gap by employing the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method. The DEMATEL approach will be utilized to identify, evaluate, and prioritize key solutions for integrating bio-based and bio-inspired materials into sustainable building design within tropical monsoon climates, informed by the expertise of architectural and building material professionals. The DEMATEL method is selected for its capacity to determine causal relationships among strategies [23–25], identify crucial enablers, and assess the influence of various solutions on the integration of bio-based and bio-inspired materials into sustainable building practices. By elucidating the intricate network of cause-and-effect relationships, this methodology enables architects, designers, and policymakers to make informed, data-driven decisions and formulate effective strategies for the adoption of these sustainable materials.

The goal of this research is to develop a strategic hierarchy for prioritizing key solutions for the integration of bio-based and bio-inspired materials into sustainable building design in tropical monsoon climates, thereby contributing to global climate change mitigation efforts. To achieve this objective, the study will pursue the following aims:

- (1) To identify key solutions for the application of bio-based and bio-inspired materials in sustainable building design appropriate for tropical monsoon climates.
- (2) To identify the top most influential solutions from the integrated design strategies of key solutions.

- (3) To analyze the interdependencies of key solutions using the DEMATEL method, thereby clarifying the complex causal relationships between them.

The study is organized into six sections. It begins by providing background information and stating the research objectives. It then presents a literature review on bio-based and bio-inspired materials in building design, and key solutions for their integration in tropical monsoon climates. The research methodology, including instrument development, expert interviews, and the DEMATEL technique, is described in Section 3. Section 4 presents the results of the DEMATEL analysis, which quantifies the interrelationships between the solutions. A discussion and interpretation of these results within the context of existing literature is provided in Section 5. The study concludes with a summary of the main findings, a discussion of limitations, and suggestions for future research.

2. Literature Review and Research Gaps

2.1. Past Studies on Bio-Based or Bio-Inspired Materials in Building Design and Construction

The urgency of mitigating the environmental impact of the building sector has spurred significant research into alternative materials and design strategies. Bio-based and bio-inspired materials offer promising avenues for creating more sustainable and resilient built environments [11,13,26]. This section synthesizes key findings from previous studies, highlighting common themes in the exploration and application of these innovative approaches in building design and construction. The main research themes identified encompass: (1) material diversity and property characterization; (2) building performance, applications, and energy efficiency; (3) sustainability assessment, life cycle analysis, and circularity; (4) bio-inspiration and biomimicry in design; (5) challenges, barriers to bio-based and bio-inspired construction materials; and (6) the role of policy and technological advancements.

2.1.1. Material Diversity and Property Characterization

A significant body of research focuses on identifying, developing, and characterizing a wide array of bio-based materials for construction. Traditional materials like wood/timber and bamboo, including engineered forms like mass timber, laminated bamboo, and bamboo scrimber, are extensively studied for their structural and insulation properties [13,16,27]. Emerging materials such as mycelium composites are explored for insulation and other unique attributes like bioremediation potential [13,28–30]. Plant-based agricultural fibers and residues, including hemp, cork, straw, alfa, date palm wood, corn pith/cobs, groundnut shells, coir, and sawdust, are investigated, often as aggregates or reinforcements in composites or insulation panels [16,31–33]. Earth construction techniques, often incorporating plant aggregates, are re-evaluated for their low environmental impact [34–36]. Research efforts concentrate on quantifying key properties essential for building performance, such as thermal conductivity [37,38], hygrothermal behavior including moisture buffering capacity and response to humidity changes [14,15,39,40], mechanical strength and stiffness [41,42], durability and resistance to degradation [43,44], fire performance [31], and acoustic absorption [45]. Studies also highlight the importance of pre- and post-treatments or specific manufacturing processes (like reinforcement or creating composites) to optimize these properties and overcome inherent limitations [44–46], aiming to tailor material characteristics for specific applications [47].

2.1.2. Building Performance, Applications, and Energy Efficiency

Numerous studies evaluate the performance of bio-based and bio-inspired materials within building systems, focusing primarily on energy efficiency and occupant comfort. Insulation is a major application area, with research comparing the thermal and hygrothermal performance of various bio-based options (mycelium, wood fiber, hemp, cork, corn-based

materials, agricultural waste composites) against conventional insulators like polyurethane or polystyrene foam [28,31,32,37–39]. Studies often highlight the significant role of moisture transfer and latent heat effects in bio-based materials, which can influence dynamic thermal performance and condensation risk, necessitating careful design and simulation [14,15,33,40]. In this context, the presence of thermal bridges, discontinuities in the insulation layer, represents a major technical challenge. These bridges lead to localized drops in internal surface temperatures, significantly increasing the risk of inner surface condensation and subsequent mold growth, even when the overall insulation thickness is optimized [10]. Optimized insulation thickness is crucial for balancing energy savings and preventing moisture issues [15,30]. In structural applications, engineered timber and bamboo demonstrate viability for larger structures and prefabricated elements like shear walls, though performance relative to traditional materials varies [38,42,44,46,48]. Facades and cladding systems utilize bio-based materials, biopolymers, and vertical greenery systems (VGS) to improve thermal performance, reduce cooling loads, enhance air quality, manage rainwater, and contribute esthetic value [49–56]. VGS, in particular, provide cooling through shading and evapotranspiration [55]. Bio-inspired approaches contribute to adaptive building envelopes, with mechanisms for responsive shading based on plant or animal strategies, significantly reducing energy consumption for cooling while maintaining daylighting [47,57–59]. Passive cooling techniques, including material selection and strategies like night ventilation, are explored to minimize reliance on active systems [60–62]. Water management is addressed through bio-inspired water harvesting surfaces [63–65], bio-based filtration systems using agricultural waste [66], and integrated designs incorporating green roofs and smart water management [67,68]. Overall, integrating bio-based materials and bio-inspired designs shows potential for significant energy savings and improved indoor environmental quality [55,69].

2.1.3. Sustainability Assessment, Life Cycle Analysis, and Circularity

A critical driver for adopting bio-based materials is their perceived environmental benefit, frequently assessed using LCA and LCCA [15,70,71]. Studies consistently show that increasing bio-based material content generally reduces a building's climate impact (Global Warming Potential—GWP) compared to conventional materials like concrete, steel, fired bricks, or fossil-fuel-based foams, particularly when accounting for biogenic carbon sequestration [12,13,31,72,73]. However, the extent of these benefits is sensitive to methodological choices, including the system boundaries, assumed end-of-life scenarios (reuse, recycling, energy recovery, landfilling), the time horizon considered (especially for dynamic LCA), and allocation methods [15,74]. Extending building service life or ensuring continued carbon storage post-demolition can further enhance climate benefits [72,75]. While often reducing initial production costs and climate/resource depletion impacts [12,76], some bio-based materials may perform worse in other environmental categories like eutrophication or land use, and may not always be the most economically viable option across the entire life cycle without optimization [12,15]. Robust optimization methods are employed to identify solutions balancing cost-effectiveness and environmental performance, often suggesting combinations like bio-based insulation with renewable heating systems [71]. The principles of circular economy are relevant, with timber construction highlighted for its alignment with design for disassembly [77], and the utilization of agricultural or industrial waste streams contributing to resource efficiency [32,45]. Furthermore, using “green” materials can significantly reduce impacts related to toxicity [73], aligning with broader sustainable development goals [11].

2.1.4. Bio-Inspiration and Biomimicry in Design

Beyond directly using natural materials, research explores bio-inspiration and biomimicry—learning from and emulating nature’s strategies, forms, and processes—to develop innovative building solutions [26,47,64]. This involves analyzing adaptation strategies of plants and animals to diverse climates and functions [47,63] and translating these into technical applications [47,58]. Examples include developing weather-responsive building components that change shape based on humidity, inspired by plant movements, potentially using 4D printing techniques [57]; designing materials with optimized microstructures for enhanced mechanical properties like stiffness and toughness, mimicking biological materials [41]; creating surfaces inspired by organisms like spider silk, cacti, or Namib desert beetles for efficient atmospheric water harvesting [63–65]; and developing biomimetic adaptive shading systems inspired by cacti or the movement of plants like *Mimosa pudica* to regulate solar gain and improve thermal comfort [69]. Integrated multiple bio-inspired mechanisms into single, multi-functional building envelope systems [58] and utilizes parametric and generative design tools to implement complex, adaptive patterns [59,78]. The overarching goal is to create “smart” or active materials and systems that effectively regulate indoor conditions (humidity, temperature, light, CO₂), filter pollutants, and possess properties like self-cleaning or self-healing, leading to more resilient and efficient buildings [57].

2.1.5. Challenges, Barriers to Bio-Based and Bio-Inspired Construction Materials in Tropical Monsoon Climates

Despite the demonstrated potential, several challenges and barriers hinder the widespread adoption and upscaling of bio-based and bio-inspired construction materials and techniques [74], particularly when compared to established building envelope solutions that have rigorous standards for building physics and material performance [10]. A significant gap often exists between laboratory-level advancements and practical, large-scale implementation in real architectural contexts [26]. Key barriers identified include difficulties in upscaling production for emerging materials [29], concerns regarding initial costs compared to conventional options [12], and a lack of awareness, knowledge, and experience among construction professionals [74]. Standardization, material certification, accreditation, and consistent LCA methodologies are often lacking, creating uncertainty for designers and specifiers [31,79]. Policy and regulatory frameworks may not adequately support or incentivize the use of these materials, and market inertia or vested interests can impede adoption [74,79]. The issues of bio-based materials in construction are even more challenging in tropical monsoon climates, where technical challenges remain regarding long-term durability, moisture management in high climatic temperatures, localized cooling at thermal bridges, and mold growth driven by the specific eco-physiological conditions of microorganisms inhabiting exterior façades, fire resistance optimization, and ensuring sustainable sourcing (e.g., avoiding illegal deforestation for timber) [15,20,40,43]. Additionally, the energy consumption associated with manufacturing certain bio-composites needs attention [29]. Proposed solutions include developing more case studies and demonstration projects [74,79], implementing supportive policies, standards, and financial incentives [31,79], promoting regional economic development through local resource utilization [37], enhancing education and training [74], fostering collaboration between researchers and industry [79], advancing simulation tools for hygrothermal performance and optimization [40], and continuing research into material optimization, innovative fabrication [57], and bio-inspired design integration [41,47,65].

2.1.6. The Role of Policy and Technological Advancements

Policy and technological advancements play a crucial role in advancing the adoption of these sustainable materials. Implementing supportive building codes, offering incentives, and promoting research and development are essential for mainstreaming bio-based construction [31,79]. The development of innovative fabrication technologies, such as additive manufacturing for custom-made natural fiber composites [57], and the exploration of multi-functional biomimetic adaptive building envelopes [58] highlight the potential of technological innovation. Furthermore, promoting prefabricated construction using bio-based composites can minimize construction waste and carbon emissions [79]. The integration of advanced design and hygrothermal performance simulation tools is also crucial for predicting and managing moisture-related issues in building envelopes, especially in humid climates [40]. In addition, ensuring the supply of local bio-based raw materials is also a prerequisite for maintaining long-term design strategies. It is necessary to consider and plan areas for bio-based raw materials to ensure the conservation of land, water, and forest resources. Long-life cycle materials but short growth time such as bamboo for modified bamboo products is a solution that meets both good mechanical properties and minimize life cycle emissions, growing well in tropical climates [80]. Output materials from agricultural products to be used as sustainable sources also require manage in supply chain, creating ecosystems and strengthening strategies for reuse, recycling and maintenance techniques of construction structures from local biological materials [81,82].

2.2. Identifying Key Solutions for Integrating Bio-Based and Bio-Inspired Materials into Sustainable Building Design Practices in Tropical Monsoon Climates

Integrating bio-based and bio-inspired materials into building practices for tropical monsoon climates requires strategies tailored to high heat, humidity, and intense rainfall, while leveraging abundant local resources. Based on the reviewed literature, this study identified ten key solutions which aim to enhance thermal comfort, manage moisture, conserve resources, and improve building resilience in challenging tropical monsoon environments:

S1: Design for natural ventilation with bio-based screens and passive cooling: In hot and humid tropical monsoon climates, maximizing passive cooling is crucial [60,62]. Designing building layouts for effective cross-ventilation, potentially guided by night ventilation strategies [39,61], can significantly reduce reliance on active cooling. Utilizing locally available bio-based materials like bamboo or woven timber/palm leaves [16,42,83] for permeable screens or facade elements allows airflow while providing essential shading [49,55]. This approach mimics natural ventilation strategies [47], and leverages the inherent properties of bio-based materials to create comfortable indoor environments without excessive energy consumption, addressing a key recommendation from studies showing insulation alone may hinder heat evacuation without proper ventilation [39].

S2: Implement rainwater harvesting with bio-inspired roof systems: Tropical monsoon climates experience intense rainfall, presenting an opportunity for water harvesting. Designing roof forms inspired by the water-collecting efficiencies of natural organisms can optimize rainwater capture [63–65]. Integrating this with green roof systems using locally sourced [52,53,67,68], water-tolerant bio-based substrates can further enhance water management by reducing runoff and providing significant evaporative cooling benefits [55,56,68]. This synergistic approach addresses both water conservation and thermal comfort, turning a climatic challenge into a resource opportunity [67,68].

S3: Utilize mycelium-based insulation for humidity control: High ambient humidity necessitates careful material selection for building envelopes. Mycelium-based composites offer promising insulation properties [13,28,30] and, like many bio-based materials, possess inherent hygroscopic qualities or moisture buffering capacity that can help regu-

late indoor humidity levels [14,31,39]. Designing wall and roof assemblies with mycelium insulation [28,30], requires addressing both condensation on the inner surface of the partition and inter-layer condensation within the envelope. Ensuring adequate vapor permeability is crucial to leverage this benefit and prevent condensation issues, which can be a risk in humid climates, especially with thick insulation layers [15]. While production challenges exist [29], mycelium's potential for passive humidity control makes it suitable for tropical conditions [28].

S4: Employ bamboo reinforced composite structures: Bamboo is a rapidly renewable resource abundant in many tropical regions [43]. Utilizing it in engineered forms, such as fiber-reinforced composites or laminated elements [44,46], offers a sustainable alternative to conventional structural materials like steel and concrete. These bamboo composites can provide adequate strength and stiffness [42], potentially with treatments to enhance durability and bond strength [46]. While conventional mineral wool insulation suffers from significant loss in mechanical stability and thermal efficiency when its durability is compromised [84], the structural viability of bamboo elements is maintained by optimizing their resistance to moisture-induced degradation. Designing modular or prefabricated bamboo structural systems can improve construction efficiency and adaptability, making sustainable, resilient housing more accessible, particularly in low-cost contexts [79], though thermal performance might need consideration compared to wood [38].

S5: Integrate bio-inspired self-shading systems: Controlling solar gain is critical for reducing cooling loads in sunny tropical climates. Bio-inspired design offers pathways to create dynamic, adaptive shading systems that respond to environmental conditions, mimicking mechanisms found in plants [47,57]. These systems can range from humidity-responsive wood composites to more complex kinetic patterns implemented through parametric design [58,59], potentially using materials like bamboo or timber louvers [83]. Such biomimetic shading skins can significantly reduce energy consumption for cooling while maintaining adequate daylighting and enhancing visual comfort [55,69].

S6: Develop bio-composite exterior cladding for weather resistance: Building envelopes in monsoon climates must withstand heavy rain and high humidity. Developing exterior cladding panels using bio-composites [50,70] derived from locally abundant agricultural residues (e.g., coconut coir, groundnut shells, rice husks) mixed with natural or bio-based resins offers a sustainable and potentially cost-effective solution [12,32]. These composites can be engineered for durability and weather resistance [45]. Compared to conventional synthetic materials like expanded polystyrene, which undergo property degradation when exposed to solar radiation in real aging conditions, the longevity of bio-composites is ensured through a systemic hygrothermal design [85]. Proper design, including ventilated air gaps behind the cladding [51], is essential to promote drying and prevent moisture accumulation within the wall assembly [40], ensuring the longevity of the bio-based materials [43].

S7: Utilize earth-based building materials with natural stabilizers: Earth construction techniques like rammed earth or adobe utilize readily available local materials with low embodied energy [34]. Incorporating natural stabilizers such as plant fibers (straw, hemp) or lime can enhance the durability and moisture resistance of earth walls [35], making them more suitable for the humid and wet conditions of monsoon climates. Addressing the durability of these materials is crucial, as even established conventional insulators lose their effectiveness over time if not properly protected from environmental stressors [84]. Building design should incorporate features like adequate roof overhangs and foundation details to protect earthen walls from direct rain and ground moisture [40,43]. When properly designed and protected, earth construction offers a highly sustainable building approach [34].

S8: Design with living building systems: Integrating vegetation directly onto the building envelope through living walls or green facades provides multiple benefits in tropical climates [52–54]. Using carefully selected local plant species adapted to the climate enhances evaporative cooling, reduces surface temperatures, improves air quality, and supports biodiversity [55,56]. These living systems can be part of a broader “living building” approach [73], potentially incorporating aquaponics or integrated water processing systems to create highly sustainable, regenerative buildings well-suited to tropical ecosystems [54].

S9: Implement bio-based water filtration systems: Leveraging abundant rainfall requires effective water treatment for reuse. Simple, low-cost water filtration systems can be constructed using locally available bio-based materials like sand, gravel, activated carbon derived from agricultural waste (e.g., coconut coir), and specific plant materials [66]. Integrating such systems into building design allows for the purification of harvested rainwater or greywater, reducing reliance on municipal supplies and promoting water self-sufficiency, a key aspect of sustainable water management in green buildings [66,67].

S10: Promote use of locally harvested timber with sustainable practices: Timber is a traditional and effective building material in many tropical regions [83]. Utilizing locally sourced timber, ideally employing species adapted to the climate, connects buildings to their context and often supports local economies [43,83]. Ensuring sustainable forestry practices is paramount to avoid deforestation and maintain ecological balance [83]. Promoting modern engineered timber products (like mass timber where appropriate [27]) alongside traditional joinery techniques can offer versatile, low-carbon structural and finishing solutions [27,83], aligning with circular economy principles like design for disassembly [77] and leveraging timber’s positive environmental profile [27].

2.3. Research Gaps

Although exploration into the potential of bio-based and bio-inspired materials for sustainable building design is increasing, three critical research gaps require attention.

Firstly, there is a lack of integrated strategies specifically tailored to the application of bio-based and bio-inspired materials in sustainable building design under tropical monsoon climates, highlighting the need to identify key solutions suitable for this context: While the reviewed literature extensively covers the properties and applications of various bio-based and bio-inspired materials [13,16,28,31,46] and explores performance aspects like hygrothermal behavior [14,15,33,39,40] and passive cooling [60,62], there appears to be a gap in research that holistically integrates multiple strategies specifically tailored for the unique challenges of tropical monsoon climates. This climate presents a demanding combination of high heat, intense solar radiation, extreme humidity, and heavy seasonal rainfall. Much existing research focuses on individual material performance [32,37,45], specific systems like VGS [52,53] or water harvesting [63,64], or performance in different climate types (e.g., semiarid [15], general warm climates [62]). A systematic investigation into the optimal combination and integration of diverse bio-based and bio-inspired solutions (materials, passive design, water management, adaptive systems) designed explicitly to address the simultaneous climatic stresses of tropical monsoons remains relatively unexplored.

Secondly, limited exploration of practitioner perspectives using structured decision-making models: Although barriers to adoption related to knowledge gaps and industry perspectives have been identified [26,74,79], the application of structured multi-criteria decision-making (MCDM) methods like DEMATEL (Decision Making Trial and Evaluation Laboratory) to capture and analyze the nuanced perspectives of senior practicing architects specifically regarding integration strategies in this climatic context seems novel. Previous studies often rely on laboratory testing [33,39,45], simulations [15,30,61,69,86], LCA/LCCA [71–73], or general surveys/interviews about barriers [74]. The DEMATEL ap-

proach focuses on understanding the causal relationships and interdependencies between different potential solutions, providing insight into which strategies architects perceive as most influential or foundational for successful integration in challenging monsoon climates. This specific methodological approach, applied to experienced practitioners in this niche, represents a gap in understanding the practical decision-making hierarchies for implementing these sustainable solutions.

Thirdly, lack of understanding interdependencies and synergies/conflicts between solutions: The proposed study aims to identify key solutions, but the existing literature often examines these solutions somewhat in isolation. For instance, studies might focus on insulation performance [15,31], structural applications [42,46], shading [58,69], or water management [66,68]. A research gap exists in comprehensively understanding the interdependencies, potential synergies, and potential conflicts when multiple bio-based and bio-inspired solutions are implemented concurrently within the same building system, particularly under monsoon conditions. Analyzing these interactions, informed by the causal relationships identified through DEMATEL from experienced architects, could fill a crucial gap needed to move from component-level research to effective whole-building design integration.

3. Research Methodology

3.1. The DEMATEL Method

The DEMATEL method is employed to analyze the interdependencies among complex factors within a system [87,88]. Unlike methods that only prioritize factors, DEMATEL identifies cause-and-effect relationships, providing deeper insights into complex decision-making scenarios [89]. In this study, DEMATEL was used to examine the interdependencies among ten key solutions for integrating bio-based and bio-inspired materials into sustainable building design in tropical monsoon climates. The DEMATEL method was applied through the steps outlined below and illustrated in Figure 1.

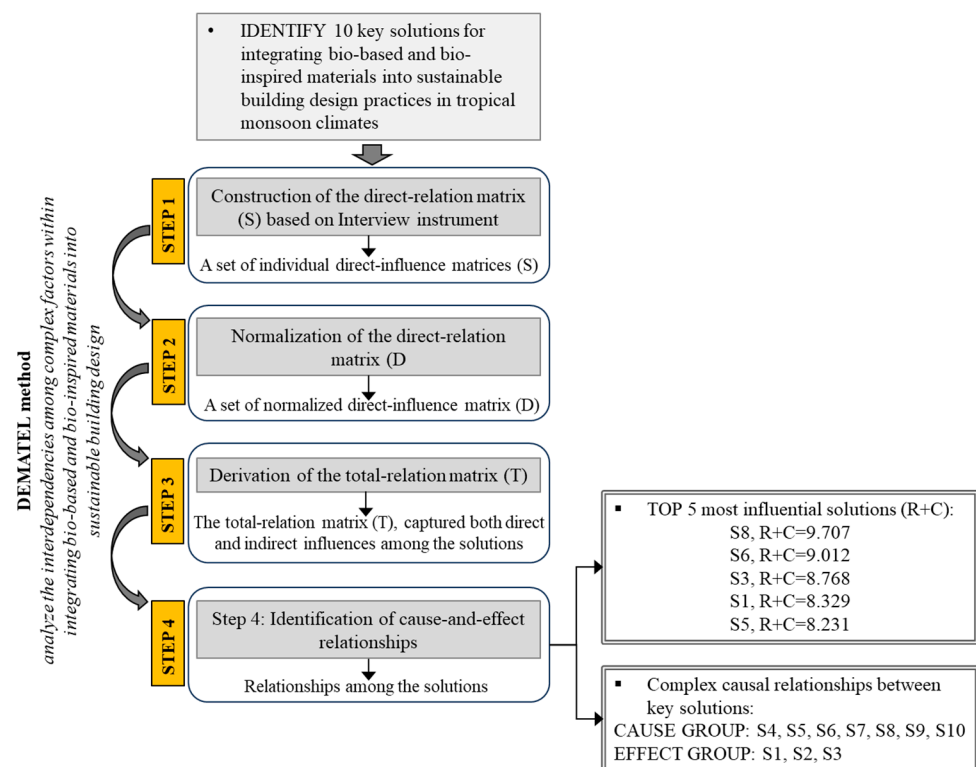


Figure 1. Research framework of this study.

3.1.1. Step 1: Construction of the Direct-Relation Matrix (S)

A direct-relation matrix (S) was developed based on expert evaluations. Twenty-one provided pairwise comparisons of the ten proposed solutions, rating the degree to which each solution S_i directly influences another solution, S_j . This was performed using a five-point integer scale: 0 (no influence), 1 (low influence), 2 (medium influence), 3 (high influence), and 4 (very high influence). The outcome was a set of individual direct-influence matrices, $X = [x_{ij}]$, where x_{ij} represents the degree to which solution S_i influences solution S_j [90]. These matrices were then averaged to produce a single composite direct-relation matrix, denoted as S, as shown in Equation (1):

$$S_{ij} = \frac{1}{21} \sum_{k=1}^{21} S_{ij}^k; \text{ with } i, j = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, \quad (1)$$

3.1.2. Step 2: Normalization of the Direct-Relation Matrix (D)

The direct-relation matrix (S) was normalized to create the normalized direct-influence matrix (D). This normalization was achieved by dividing each element of S by the maximum row or column sum, as defined in Equation (2):

$$D = \frac{S}{m}, \quad (2)$$

where

$$m = \max \left(\max_{1 \leq j \leq 10} \sum_{i=1}^{10} S_{ij}, \max_{1 \leq i \leq 10} \sum_{j=1}^{10} S_{ij} \right), \quad (3)$$

3.1.3. Step 3: Derivation of the Total-Relation Matrix (T)

The total-relation matrix T was calculated to capture both direct and indirect influences among the solutions. This was achieved by applying a matrix operation to D, incorporating indirect effects through an infinite series approximation. The computation followed the standard DEMATEL formulation provided in Equation (4):

$$T = D(I - D)^{-1}, \quad (4)$$

where I matrix is the identity matrix. This transformation accounted for all possible interactions between solutions, revealing both immediate and cascading influences

3.1.4. Step 4: Identification of Cause-and-Effect Relationships

To analyze the relationships among the solutions, the sum of rows (R) and the sum of columns (C) of the total-relation matrix (T) were calculated using Equations (5) and (6), respectively.

$$R = [r_i]_{10 \times 1} = \left[\sum_{j=1}^{10} t_{ij} \right]_{10 \times 1}, \quad (5)$$

$$C = [c_j]_{1 \times 10} = \left[\sum_{i=1}^{10} t_{ij} \right]_{1 \times 10}, \quad (6)$$

in which:

r_i is the total direct and indirect effect exerted by solution S_i on other solutions.

c_j is the total direct and indirect effect that solution S_j receives from other solutions.

From these, two key indicators were derived: the prominence ($R + C$) represents the overall importance of each solution in the system, while the relation ($R - C$) represents the net influence of each solution (i.e., whether a solution is a cause (positive value) or an effect (negative value)).

A causal diagram was generated by plotting the prominence values ($R + C$) on the horizontal axis and the relation values ($R - C$) on the vertical axis. Solutions positioned in the upper half (positive $R - C$) were identified as cause solutions, those that significantly affect others, while those in the lower half (negative $R - C$) were classified as effect solutions, those primarily shaped by external influences [91]. This diagram visually encapsulates the system's structure, offering valuable insights into the hierarchy and influence pathways among the solutions. Consequently, it supports the strategic prioritization of interventions to facilitate the integration of bio-based and bio-inspired materials into sustainable building practices tailored for tropical monsoon climates.

3.2. Interview Instrument Development and Data Collection

The development of the interview instrument and the subsequent data collection process for this study were carefully designed to ensure methodological rigor and relevance to the research objectives. After identifying ten key solutions for integrating bio-based and bio-inspired materials into sustainable building design in tropical monsoon climates, a structured questionnaire was created to support a detailed expert evaluation using the DEMATEL method. The questionnaire consisted of two main sections. The first section focused on gathering demographic and professional background data, such as academic qualifications, age, years of experience, organizational affiliation, professional roles, and areas of expertise. This information was essential to validate the qualifications of participating experts and to contextualize their evaluations. The second section of the questionnaire operationalized the DEMATEL approach to capture the perceived interrelationships among the ten proposed strategies. Experts were asked to assess the direct influence of each solution on all others using a five-level scale: 0 (no influence), 1 (low influence), 2 (medium influence), 3 (high influence), and 4 (very high influence). This pairwise comparison method allowed for the construction of a direct-relation matrix, which quantitatively represented the degree of influence each solution exerted over others. This matrix served as a crucial input for further DEMATEL analysis, facilitating the identification of cause-effect chains and priority areas in the adoption of bio-based and bio-inspired solutions.

Prior to full deployment, a pilot test was conducted to validate and refine the questionnaire. Two senior architects and one expert in bio-based building materials were consulted during this phase. Their feedback helped to enhance the clarity and relevance of the instrument, ensuring its suitability for expert evaluation. Minor adjustments were made to improve terminology consistency and align the scale with participants' practical understanding.

Data collection involved structured interviews conducted with twenty-one experts in Vietnam between January and March 2025. Potential participants were carefully selected based on predefined criteria to ensure deep expertise and relevant experience. The inclusion criteria stipulated that experts must possess: (1) a minimum of ten years of experience in architectural building design or building materials; (2) demonstrable expertise in bio-based and/or bio-inspired building materials; and (3) a clear understanding of sustainable design principles specifically within the context of tropical monsoon climates. A targeted recruitment strategy using snowball sampling was employed. Initial experts meeting all criteria were identified and invited to participate; they were then asked to recommend other qualified professionals from their academic and industry networks. This approach proved effective in accessing a highly knowledgeable and relevant cohort of participants.

The structured interviews were scheduled in advance, with the interview instrument shared beforehand to allow participants adequate time for preparation. During the interviews, each expert first completed the demographic section before proceeding to the DEMATEL-based assessment. Experts filled out the direct-influence matrix in a guided, face-to-face format, ensuring accuracy and consistency across responses. Each interview

lasted approximately 60 min, allowing sufficient time for clarification and in-depth discussion when needed. This comprehensive and systematic approach enabled the collection of robust, high-quality data that forms the empirical basis for the study's analytical findings.

As provided in Table 1, the profiles of twenty-one experts represented a balanced blend of academic and professional sectors, with many holding dual roles in universities and architectural or design firms. This dual affiliation provided a unique intersection of theoretical insight and practical application, which is vital for evaluating the feasibility and impact of bio-based and bio-inspired materials in real-world building design. The qualifications of the participants further support the credibility of the findings. The group included two full or associate professors, multiple Ph.D. holders, and experienced professionals with master's degrees. Their areas of expertise spanned architecture, civil engineering, environmental engineering, material science, and urban planning, fields directly relevant to sustainable building design. On average, the experts had over 17 years of professional experience, with the most experienced contributor having 29 years in the field. The breadth and depth of this experience base ensure that the insights drawn from the DEMATEL analysis are grounded in both academic rigor and practical knowledge of the challenges and opportunities unique to tropical monsoon climates.

Table 1. Overview of expert interview profiles.

Expert ID	Qualification	Age	Years of Experience	Organization	Position	Expertise
E1	Ph.D	45	20	University, and Architecture and design firm	Lecturer, and Architectural design specialist	Architecture
E2	Ph.D	36	10	University, and Architecture and design firm	Lecturer, and Architectural design specialist	Architectural engineering
E3	Assoc. Prof., Ph.D	49	25	University, and Architecture and design firm	Lecturer, and Architectural design specialist	Architecture and urban planning
E4	MSc	50	26	Architecture and design firm	Project manager	Civil engineering
E5	MSc	36	10	University, and Architecture and design firm	Lecturer, and Architectural design specialist	Architecture
E6	Ph.D	46	22	University	Lecturer	Material engineering
E7	MSc	40	15	University	Researcher	Built environment
E8	MSc	35	10	University, and Architecture and design firm	Lecturer, and Architectural design specialist	Architecture
E9	Dr.	34	10	University, and Architecture and design firm	Lecturer, and Architectural design specialist	Architectural engineering
E10	MSc	42	18	University, and Architecture and design firm	Lecturer, and Architectural design specialist	Architecture

Table 1. Cont.

Expert ID	Qualification	Age	Years of Experience	Organization	Position	Expertise
E11	MSc	41	18	University, and Architecture and design firm	Lecturer, and Architectural design specialist	Architecture
E12	MSc	43	18	University	Lecturer	Environmental engineering
E13	Full Professor, Ph.D	48	24	University	Lecturer	Building materials
E14	Ph.D	40	14	University, and Architecture and design firm	Lecturer, and Architectural design specialist	Architecture
E15	Ph.D	41	15	University, and Architecture and design firm	Lecturer, and Architectural design specialist	Architecture
E16	Assoc. Prof., Ph.D	51	28	University	Lecturer	Architecture
E17	MSc	38	12	University	Lecturer	Architecture
E18	Ph.D	42	13	University	Lecturer	Architecture
E19	Ph.D	51	29	University, and Architecture and design firm	Lecturer, and Architectural design specialist	Architecture
E20	MSc	35	10	Architecture and design firm	Architectural design specialist	Architecture
E21	MSc	42	15	Architecture and design firm	Green building consultant	Architecture

This expert diversity enhances the reliability and validity of the study's results. The varied perspectives allowed for a comprehensive assessment of the interdependencies and priorities among the identified solutions. Furthermore, the consistent involvement of participants in both teaching and architectural practice meant that their evaluations were informed by the latest academic research as well as current market and construction realities. As such, the expert input strengthens confidence in the strategic hierarchy developed, making the findings a robust foundation for guiding policy development, architectural innovation, and further research into sustainable design in tropical monsoon regions.

4. Results

This section presents the results obtained from the application of the DEMATEL methodology. The findings provide a detailed understanding of the interrelationships and dependencies among the critical solutions identified for integrating bio-based and bio-inspired materials into sustainable building design in tropical monsoon climates. Each step of the DEMATEL process and its corresponding outcome is presented below.

4.1. Results of Developing the Direct-Relation Matrix (S)

The direct-relation matrix (S) was constructed based on the expert evaluations. After collecting data from twenty-one experts, the average matrix S was computed by aggregating the individual 10×10 matrices using Equation (1). The resulting direct-relation matrix S represents the initial influence levels among the solutions, as assessed by the experts.

$$S = \begin{bmatrix} 0 & 0.810 & 2.190 & 1.714 & 2.667 & 2.143 & 1.619 & 2.476 & 0.810 & 1.381 \\ 0.762 & 0 & 1.333 & 1.286 & 1.143 & 1.714 & 1.619 & 1.714 & 2.667 & 0.667 \\ 2.286 & 1.619 & 0 & 1.905 & 1.857 & 2.714 & 0.857 & 2.429 & 0.667 & 1.333 \\ 1.619 & 1.286 & 1.952 & 0 & 1.952 & 2.095 & 2.333 & 2.095 & 0.810 & 2.000 \\ 3.000 & 1.333 & 1.905 & 1.952 & 0 & 2.000 & 2.429 & 2.429 & 0.571 & 1.667 \\ 2.286 & 1.714 & 2.810 & 2.190 & 1.905 & 0 & 1.524 & 2.476 & 1.048 & 1.476 \\ 1.619 & 1.238 & 2.143 & 2.095 & 1.476 & 2.238 & 0 & 2.714 & 1.000 & 1.143 \\ 2.857 & 1.952 & 2.714 & 2.048 & 2.476 & 2.381 & 2.381 & 0 & 1.571 & 1.190 \\ 0.762 & 2.524 & 0.714 & 0.714 & 0.524 & 0.952 & 1.048 & 1.952 & 0 & 0.619 \\ 1.238 & 0.810 & 1.429 & 1.952 & 1.762 & 1.429 & 1.095 & 1.429 & 0.500 & 0 \end{bmatrix}$$

4.2. Results of Normalizing the Direct-Influence Matrix (D)

The direct-relation matrix (S) was subsequently normalized to generate the normalized direct-influence matrix (D) using Equation (2). This normalization step ensured that the influence values were scaled appropriately for further computations.

$$D = \begin{bmatrix} 0 & 0.041 & 0.111 & 0.087 & 0.135 & 0.109 & 0.082 & 0.126 & 0.041 & 0.070 \\ 0.039 & 0 & 0.068 & 0.065 & 0.058 & 0.087 & 0.043 & 0.087 & 0.135 & 0.034 \\ 0.116 & 0.082 & 0 & 0.097 & 0.094 & 0.138 & 0.118 & 0.123 & 0.034 & 0.068 \\ 0.082 & 0.065 & 0.099 & 0 & 0.099 & 0.106 & 0.123 & 0.106 & 0.041 & 0.101 \\ 0.152 & 0.068 & 0.097 & 0.099 & 0 & 0.101 & 0.077 & 0.123 & 0.029 & 0.085 \\ 0.116 & 0.087 & 0.143 & 0.111 & 0.079 & 0 & 0.111 & 0.126 & 0.053 & 0.075 \\ 0.082 & 0.063 & 0.109 & 0.106 & 0.075 & 0.114 & 0 & 0.138 & 0.051 & 0.058 \\ 0.145 & 0.099 & 0.138 & 0.104 & 0.126 & 0.121 & 0.121 & 0 & 0.080 & 0.060 \\ 0.039 & 0.128 & 0.036 & 0.036 & 0.027 & 0.048 & 0.053 & 0.099 & 0 & 0.031 \\ 0.063 & 0.041 & 0.072 & 0.099 & 0.089 & 0.072 & 0.056 & 0.072 & 0.025 & 0 \end{bmatrix}$$

4.3. Results of Generating the Total-Relation Matrix (T)

The total-relation matrix (T) was then derived using Equation (4). This matrix captures both direct and indirect influences among the solutions, providing a comprehensive view of their interrelationships.

$$T = \begin{bmatrix} 0.373 & 0.322 & \mathbf{0.483} & \mathbf{0.429} & \mathbf{0.473} & \mathbf{0.484} & \mathbf{0.422} & \mathbf{0.530} & 0.245 & 0.324 \\ 0.304 & 0.214 & 0.338 & 0.311 & 0.306 & 0.359 & 0.293 & 0.385 & 0.280 & 0.219 \\ \mathbf{0.499} & 0.376 & \mathbf{0.410} & \mathbf{0.461} & \mathbf{0.462} & \mathbf{0.535} & \mathbf{0.476} & \mathbf{0.558} & 0.257 & 0.338 \\ \mathbf{0.446} & 0.343 & \mathbf{0.473} & 0.350 & \mathbf{0.442} & \mathbf{0.483} & \mathbf{0.457} & \mathbf{0.516} & 0.248 & 0.351 \\ \mathbf{0.513} & 0.349 & \mathbf{0.480} & \mathbf{0.447} & 0.363 & \mathbf{0.488} & \mathbf{0.425} & \mathbf{0.538} & 0.241 & 0.342 \\ \mathbf{0.514} & \mathbf{0.393} & \mathbf{0.550} & \mathbf{0.487} & \mathbf{0.479} & \mathbf{0.430} & \mathbf{0.485} & \mathbf{0.577} & 0.282 & 0.355 \\ \mathbf{0.440} & 0.338 & \mathbf{0.475} & \mathbf{0.439} & \mathbf{0.416} & \mathbf{0.483} & 0.342 & \mathbf{0.534} & 0.254 & 0.308 \\ \mathbf{0.564} & \mathbf{0.425} & \mathbf{0.573} & \mathbf{0.505} & \mathbf{0.527} & \mathbf{0.565} & \mathbf{0.516} & \mathbf{0.497} & 0.321 & 0.361 \\ 0.255 & 0.290 & 0.263 & 0.242 & 0.235 & 0.276 & 0.255 & 0.339 & 0.135 & 0.181 \\ 0.334 & 0.248 & 0.351 & 0.349 & 0.343 & 0.354 & 0.310 & 0.377 & 0.178 & 0.193 \end{bmatrix}$$

4.4. Results of Determining the Cause-and-Effect Relationships

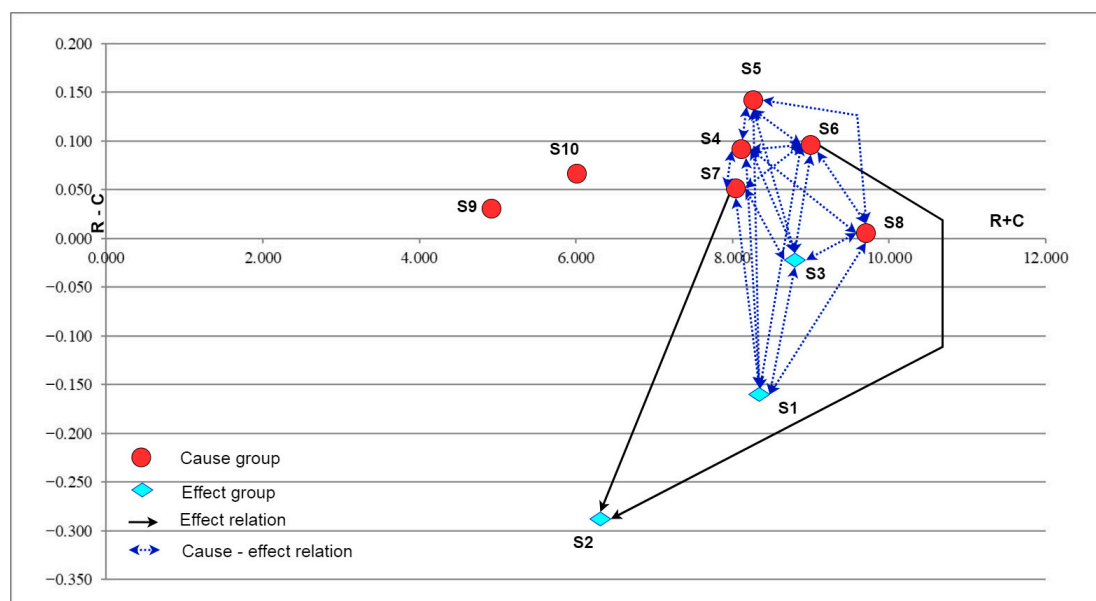
To determine the cause-and-effect relationships among the solutions, the sum of rows (R) and the sum of columns (C) were calculated using Equations (5) and (6), respectively. Subsequently, the prominence (R + C) and relation (R − C) values were computed for each solution. These results are presented in Table 2.

Table 2. The cause-and-effect relationships among identified solutions.

Solution	Ri	Ci	Ri + Ci	Rank	Ri-Ci	Identify
S1	4.085	4.244	8.329	4	−0.160	Effect
S2	3.010	3.298	6.308	8	−0.287	Effect
S3	4.373	4.396	8.768	3	−0.023	Effect
S4	4.109	4.019	8.128	6	0.090	Cause
S5	4.185	4.046	8.231	5	0.140	Cause
S6	4.554	4.458	9.012	2	0.095	Cause
S7	4.031	3.981	8.013	7	0.050	Cause
S8	4.854	4.852	9.707	1	0.002	Cause
S9	2.470	2.441	4.911	10	0.028	Cause
S10	3.037	2.972	6.009	9	0.065	Cause

As indicated in Table 2, solutions S4, S5, S6, S7, S8, S9 and S10 exhibited positive ($R - C$) values, classifying them as causal solutions. Conversely, solutions S1, S2, and S3 demonstrated negative ($R - C$) values, designating them as effect solutions.

To visualize the interdependencies among the solutions, a causal diagram was constructed. This diagram was generated by plotting the ($R + C$) values against the ($R - C$) values. Additionally, a threshold analysis was conducted to identify significant influence relationships. The threshold value, determined by calculating the average of all elements in the total-relation matrix (T), was established as 0.387. Only elements in matrix T with values exceeding this threshold were considered to represent significant influences (bolded in matrix T). This threshold analysis facilitated the identification of key influence pathways, providing a more refined understanding of the strategic interdependencies. The resulting causal and relationship diagram, illustrating the interdependencies among the ten solutions, is depicted in Figure 2.

**Figure 2.** The interdependencies among identified solutions.

5. Discussion

First observation, The DEMATEL results, as presented in Table 2 and Figure 2, yielded two key observations regarding the interrelationships and significance of the identified solutions for integrating bio-based and bio-inspired materials into sustainable building design in tropical monsoon climates.

Second observation, the prominent values ($R + C$), which represent the overall significance of each solution within the system, highlighted the most influential strategies. As shown in Table 2, the top five solutions for integrating bio-based and bio-inspired materials into sustainable building design in tropical monsoon climates were: (1) design with living building systems (S8, $R + C = 9.707$); (2) develop bio-composite exterior cladding for weather resistance (S6, $R + C = 9.012$); (3) utilize mycelium-based insulation for humidity control (S3, $R + C = 8.768$); (4) design for natural ventilation with bio-based screens and passive cooling (S1, $R + C = 8.329$); and (5) integrate bio-inspired self-shading systems (S5, $R + C = 8.231$). These prominent values indicate these solutions' overall importance and influence within the interconnected system.

Third observation, the DEMATEL model effectively categorized the solutions into "cause" and "effect" groups, providing insights into their directional influence. As depicted in Table 2 and Figure 2, seven were identified as having a causal influence: employ bamboo-reinforced composite structures (S4); integrate bio-inspired self-shading systems (S5); develop bio-composite exterior cladding for weather resistance (S6); utilize earth-based building materials with natural stabilizers (S7); design with living building systems (S8); implement bio-based water filtration systems (S9); and promote use of locally harvested timber with sustainable practices (S10). These solutions, classified within the "cause" group, were found to significantly impact on the remaining solutions, which were categorized within the "effect" group. These "effect" solutions included: design for natural ventilation with bio-based screens and passive cooling (S1); implement rainwater harvesting with bio-inspired roof systems (S2); and utilize mycelium-based insulation for humidity control (S3). This distinction between causal and effect solutions provides a structured framework for understanding the directional flow of influence and prioritizing interventions to integrate bio-based and bio-inspired materials into sustainable building design in tropical monsoon climates.

Based on the abovementioned observations, here, several interesting and noteworthy characteristics of this study were identified and discussed as follows:

Firstly, "living building systems as a central nexus in sustainable building design". Design with living building systems (S8) was ranked as the highest-priority solution for integrating bio-based and bio-inspired materials in tropical monsoon climates, despite its near-neutral $R-C$ value (0.002), suggests its central role in the network of solutions. A small $R-C$ value indicates that this solution both significantly influences other solutions and is, itself, influenced by them. In the context of sustainable building design in tropical monsoon climates, living building systems, which integrate living walls, green facades, and aquaponic systems, likely act as a nexus, enhancing the effectiveness of other solutions while simultaneously depending on their successful implementation [92]. This finding aligns with previous research which have shown that green facades and living walls improve a building's environmental performance [52], enhance thermal performance [53], and contribute to cooling and energy savings [55]. The ability of living building systems to improve air quality, reduce noise, positively affect hydrology, and provide visual benefits underscore their importance in sustainable design [52,56]. Furthermore, the life cycle assessment of living buildings reveals a substantial reduction in carcinogenic impacts when using green building materials and decentralized water systems [73], highlighting the environmental advantages of this approach. The practical challenges associated with vertical greening systems, including complex design considerations and the influence of

materials on performance [53], also imply that S8's implementation is intertwined with other solutions.

Secondly, “bio-composite cladding as a key driver of durable and resilient sustainable buildings”. The solution: develop bio-composite exterior cladding for weather resistance (S6) emerged as the second highest-priority strategy and was classified in the “cause” group, indicating its strong influence on many other solutions. Its high interconnectivity, except with S9 (bio-based water filtration systems) and S10 (locally harvested timber), suggests that it plays a foundational role in enabling broader integration of bio-based and bio-inspired materials in sustainable tropical monsoon architecture. The tropical monsoon climate, with its high humidity, intense rainfall, and fluctuating temperatures, demands resilient and moisture-tolerant envelope solutions. Bio-composite claddings made from agricultural waste fibers (like coconut coir or rice husks) and natural resins offer an environmentally responsible alternative to synthetic materials while addressing durability and thermal comfort, critical performance criteria in such climates [32,50]. Ref. [45] has shown that agricultural by-products like coir and nut shells can significantly enhance the flexural, thermal, and acoustic properties of building panels, especially when combined in hybrid forms. Moreover, the integration of ventilated cladding systems, as suggested in [40,51], can improve drying rates and prevent moisture accumulation, essential for avoiding structural degradation in humid zones. The effectiveness of this solution in influencing other design strategies lies in its dual function: it not only improves building performance but also sets a precedent for material circularity and climate-responsive envelope design. Unlike bio-based water filtration or sustainable timber practices, which are more specialized or resource-dependent, weather-resilient cladding has immediate architectural scalability and can serve as a platform for integrating additional systems such as green façades, insulation, or local biomass-based construction [12,43].

Thirdly, “focused impact and lower systemic priority of bio-based water filtration and local timber”. The lowest-priority ranking for: implement bio-based water filtration systems (S9, ranked 10th) and promote use of locally harvested timber with sustainable practices (S10, ranked 9th), despite their categorization within the influential “cause” group, stems primarily from their limited significant interactions with the other solutions analyzed within this specific network. While both solutions address fundamental aspects of sustainable building, S9 focusing on water quality using local materials like clay and activated carbon from coconut coir [66], and S10 on leveraging a renewable, performant material like timber [27,48,77], their impact, as modeled, appears more self-contained. For solution S9, while effective [66] and complementary to broader water management strategies like green roofs or greywater reuse [67,68], its direct influence on other bio-based or bio-inspired material integration strategies (beyond the filtration media itself) seems minimal in this context. It solves a crucial problem but does not necessarily catalyze a cascade of other material or design choices across the building system. Similarly, solution S10, the use of sustainably harvested local timber, is undeniably beneficial for its environmental performance [27], structural viability [83], and circularity potential [77]. However, as a specific material choice, its selection might not inherently drive or be driven by a wide array of other distinct bio-based solutions in the same way a systemic approach (like S8) or a novel composite material (like S6) does. Therefore, their “cause” status reflects their foundational nature in addressing specific needs (clean water, structural material), but their low ranking and minimal interactions suggest they operate with a more focused, rather than broadly synergistic, impact within this particular framework of interconnected solutions, making them less pivotal for unlocking widespread bio-integration across multiple domains compared to higher-ranked, more interactive solutions.

Theoretical and Practical Contributions of This Study

This study makes distinctive theoretical and practical contributions to sustainable building design, particularly for tropical monsoon climates, by advancing how MCDM methods are applied in this domain. Unlike previous MCDM-based studies, which predominantly focus on ranking green materials or technologies in isolation and treat criteria as independent, this research pioneers the targeted application of the DEMATEL technique to bio-based and bio-inspired material integration, explicitly capturing the causal interdependencies among design solutions within a climate-sensitive system. This represents a methodological shift from static prioritization toward a system-oriented cause-and-effect analysis tailored to tropical monsoon conditions. The study identifies and empirically ranks five critical solutions—living building systems, bio-composite exterior cladding, mycelium-based insulation, natural ventilation with bio-based screens, and bio-inspired self-shading systems—offering a ranked hierarchy that has not previously been established at the intersection of bio-material innovation, climatic specificity, and building design strategy. Furthermore, by classifying solutions into “cause” and “effect” groups, the study reveals novel systemic insights, notably identifying living building systems as a central nexus and bio-composite cladding as a key driving factor, thereby deepening theoretical understanding of leverage points that govern sustainability and resilience outcomes. The identification of elements with “focused impact and lower systemic priority,” such as bio-based water filtration, further refines existing knowledge by distinguishing high-influence strategies from supportive but non-driving interventions.

From a practical perspective, this study translates these theoretical advances into actionable, climate-adapted guidance for sustainable building practice. The prioritized and causally structured solution set provides architects, engineers, and designers with a clear, evidence-based decision framework that moves beyond generic sustainability checklists toward strategic intervention sequencing suitable for tropical monsoon regions. Framing living building systems as a systemic nexus and bio-composite cladding as a primary driver helps practitioners allocate resources more effectively by focusing on foundational strategies that generate cascading benefits. By integrating weather resistance, humidity control, and passive design strategies within a single causal framework, it supports a holistic and resilient design approach. These findings have direct implications for design guidelines, material selection protocols, and policy development, thereby facilitating the mainstream adoption of bio-based and bio-inspired materials in challenging climatic contexts.

6. Conclusions and Limitations

To achieve the research objectives, this study applied the DEMATEL technique to evaluate and prioritize ten key solutions for integrating bio-based and bio-inspired materials into sustainable building design in tropical monsoon climates, based on insights from twenty-one sustainable building experts. Addressing the first and second objectives, we identified a strategic hierarchy of solutions, with the top five being the following: (1) design with living building systems, (2) develop bio-composite exterior cladding for weather resistance, (3) utilize mycelium-based insulation for humidity control, (4) design for natural ventilation with bio-based screens and passive cooling, and (5) integrate bio-inspired self-shading systems. These solutions reflect a holistic approach to sustainable design, balancing material innovation with passive climate control and ecological integration.

In alignment with the third objective to analyze interdependencies, the DEMATEL model effectively categorized these strategies into “cause” and “effect” groups, revealing three noteworthy characteristics: (1) “living building systems as a central nexus in sustainable building design”, (2) “bio-composite cladding as a key driver of durable and resilient sustainable buildings” and (3) “focused impact and lower systemic priority of bio-based

water filtration and local timber”. By clarifying these causal relationships, this study provides a strategic framework for architects and policymakers to advance the integration of bio-based materials into mainstream sustainable architecture.

Despite its valuable insights, this study has certain limitations. First, the expert sample, while providing depth in practical experience, was limited to twenty-one experts and may not fully capture the perspectives of all key stakeholders. Second, while the DEMATEL method effectively maps causal relationships, it does not quantify the environmental or economic performance of the proposed solutions. Third, this study was geographically and climatically bounded to tropical monsoon regions, limiting the generalizability of the findings to other climate zones. To address these limitations, future research should pursue several avenues. First, it should aim to broaden the participatory base and validate these findings through empirical studies and quantitative assessments. Specific research questions could include the following: (1) How do the prioritized solutions perform quantitatively in terms of energy savings, thermal comfort, durability, and indoor air quality when implemented in real-world building projects across various tropical monsoon microclimates? (2) What are the comprehensive life-cycle environmental impacts (e.g., carbon footprint, resource depletion, eutrophication) and economic feasibilities (initial cost, operational savings, payback period) associated with the large-scale adoption of the top-ranked solutions like living building systems and bio-composite claddings? (3) What are the primary socio-cultural, technical, and regulatory barriers to implementing these bio-integration strategies in different tropical monsoon countries, and what policy interventions or capacity-building initiatives could facilitate their wider uptake? Addressing these questions will further strengthen the evidence base for integrating bio-based and bio-inspired materials into sustainable building practices in these critical climatic areas.

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