



# Development of Environmentally Friendly Composite Materials Biomass Fiber Based for Application Civil Engineering Structures in Earthquake-Prone Areas

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**Abstract—Development of composite materials friendly environment based fiber biomass offer opportunity significant for increase resilience structure buildings in disaster-prone areas earthquake at a time reduce dependence on synthetic materials trace carbon high. Research This aim formulate a conceptual model hybrid composite based zoning integrating function role mechanics of each type fiber biomass with matrix based geopolymer for maximize ductility, dissipation energy and stability cyclic structural materials. Research done through approach synthesis literature with examine findings empirical previously about behavior mechanic fiber bamboo, hemp, jute, ramie, sisal, kenaf, and waste agriculture in construction, as well as compatibility with system matrix innovative like geopolymers and bio-resins. Synthesis results show that design zoning that places fiber ductility high in the core and fiber zones with ability control cracks in the laminate zone external produce response more structural reliable below loading cyclic compared to approach composite one-fiber. Matrix integration geopolymer strengthen performance structure through bond good chemistry, durability high environment, and profile greater sustainability Good compared to system cement -based research this contribute in provide framework conceptual that can made into base design experiments and prototypes resistant hybrid composite earthquake based biomass. Findings This recommend validation advanced through testing mechanics, element testing scale, modeling numeric nonlinear, as well as analysis eligibility environment and economy before implementation scale field.**

**Keywords— Biomass Fiber; Hybrid Composite; Geopolymer; Earthquake Resistance**



## I. INTRODUCTION

Biomass fiber-based composite materials (natural fiber composites, NFC) are a promising sustainable alternative to synthetic fibers such as glass or carbon due to their renewable raw materials, carbon sequestration potential, and lower lifecycle energy footprint. Experimental studies have shown that NFC processed using techniques such as resin-infusion and surface treatment can improve mechanical strength, thermal resistance, and stability, making them suitable for lightweight structural applications such as renewable energy infrastructure (Owen et al., 2025). Challenges remain regarding durability and quality consistency, especially under extreme environmental conditions, so developing hybrids with synthetic fibers is a strategy to combine these advantages while maintaining sustainability (Ismail et al., 2022).

Furthermore, innovations such as adhesive-free lamination using biomass waste and surface modification with nanoparticles have been shown to improve the strength, dimensional stability, and moisture resistance of several types of NFC (Q. Wang et al., 2024). However, moisture absorption remains a crucial issue as it can reduce tensile strength by up to 40% and elastic modulus by up to 30%, although alkali and silane treatments can reduce degradation when applied optimally (Pavlovic et al., 2025). This situation emphasizes the

need for material design innovation to ensure NFC remains stable in environments with high humidity fluctuations.

Several studies have emphasized that fiber manufacturing techniques and surface modification significantly influence the adhesion between the fiber and the polymer matrix, which in turn improves mechanical properties and wear resistance (Kumar et al., 2021). NFC also offers lightweight, low-cost, and environmentally friendly characteristics, making it a potential material for automotive, furniture, and lightweight construction, with development opportunities through innovative fiber design and treatment (Dev et al., 2023). In the civil engineering field, interest in NFC is growing due to its ability to improve structural performance without compromising the principles of sustainable development.

Reinforcement of concrete structures using Corn Straw Fiber and pozzolanic materials (Corn Straw Ash) has shown increased fatigue resistance and compressive strength during dynamic earthquake loading (Peng et al., 2025). Date Palm Fiber also exhibits increased energy absorption and lightweight advantages that reduce the dead load of the structure, although challenges related to durability during repeated loading cycles still need to be addressed (Adamu et al., 2022). This confirms the relevance of biomass fiber as a potential material for seismic mitigation applications.

Received 03 January 2026, Revised 12 January 2026, Accepted 01 February 2026.

DOI:



The use of engineered cementitious composites (ECC) based on natural fibers and biochar has been shown to improve energy dissipation and strength retention during cyclic loading (Dadkhah & Tulliani, 2022). The integration of biomass materials with high-performance composites such as FRP and bio-based carbon also contributes to increased flexibility and energy dissipation capacity, which are key focuses in the design of modern earthquake-resistant structures. Recent research also highlights the need for consistent design standards and fabrication methods to ensure the long-term quality and performance of biomass-based composite materials in civil engineering structural applications (Brefo & Yakin, 2025).

Biomass fibers such as ramie, hemp, jute, kenaf, sisal, and bamboo have been reported to increase the energy absorption capacity and deformation stability of structures, especially in thin layered elements and biomimetic structures with fractal patterns (Lin et al., 2024; Chen et al., 2024). Continuous fiber composites with shape memory effects also exhibit good energy absorption capabilities and shape recovery after repeated loading cycles (Dong et al., 2023). Parameters such as fiber type, surface treatment, volume fraction, and fabrication technique significantly determine the flexural performance and energy dissipation of composites (Fath et al., 2025).

Based on the literature mapping, it can be identified that NFC research for earthquake resistance is still predominantly focused on the use of one type of fiber or one reinforcement mechanism, so there is no biomass-based composite approach that integrates internal and external reinforcement simultaneously to produce *ductile-controlled structural behavior* during cyclic loading. The novelty of this research lies in the formulation of a conceptual model of a biomass fiber-based hybrid composite with structural function zoning, namely material core reinforcement for ductility and energy dissipation and surface reinforcement for increasing flexural strength and limiting crack opening. The purpose of this research is to formulate a conceptual model of a biomass fiber-based hybrid composite for civil engineering structures in earthquake-prone areas through literature analysis and synthesis of material mechanical contributions based on zoning functions, as a scientific basis towards the development of sustainable composite materials for structural implementation and further experimental studies.

## II. METHOD RESEARCH

This study applies a conceptual analysis approach based on literature studies to formulate a model for a biomass fiber-based hybrid composite material for civil engineering structures in earthquake-prone areas. This approach was chosen because the focus of the research is not on laboratory testing or numerical modeling, but rather on the theoretical development of material design through a synthesis of scientific findings regarding the characteristics of biomass fibers, composite reinforcement mechanisms, and the performance requirements of earthquake-resistant structures.

Literature selection was conducted based on thematic relevance, with priority given to publications discussing the contribution of biomass fibers to increasing flexural strength, ductility, energy dissipation, or strength retention during cyclic loading. The analysis was conducted thematically and comparatively, grouping previous research findings based on fiber type, matrix type, manufacturing technique, and internal and external reinforcement mechanisms, then critically comparing their advantages and limitations.

The analysis results are synthesized argumentatively-deductively to formulate design parameters for a biomass fiber-based hybrid composite model. These parameters include internal reinforcement functions for ductility and energy dissipation, external reinforcement functions for increasing flexural capacity and limiting crack opening, as well as the suitability of the matrix and manufacturing techniques so that both mechanisms can work simultaneously during earthquake loading. The output of this method is a conceptual model of a hybrid composite based on mechanical function zoning, which serves as a scientific basis for further research through laboratory testing, numerical simulations, or structural implementation.

## III. RESULT AND DISCUSSION

Literature synthesis results indicate that the performance of biomass fiber-based composite materials for civil engineering structural applications in earthquake-prone areas is strongly influenced by the mechanical characteristics of each fiber and its response to dynamic loading. A comprehensive study of *natural fiber biocomposites* confirms that plant fibers can increase the tensile strength, flexural strength, and toughness of concrete and mortar, although the strengthening effect is highly dependent on the fiber type, volume fraction, and quality of the fiber-matrix bond (Olanrewaju et al., 2025). In the context of repetitive and dynamic earthquake loads, these characteristics are crucial because structural materials are required to maintain energy absorption and post-cracking capacity to prevent brittle failure modes.

Findings from recent studies of *natural fiber reinforced concrete (NFRC)* tested under *impact* and cyclic loads indicate a consistent pattern: the addition of natural fibers increases energy absorption capacity, delays initial crack initiation, and shifts the failure mode from brittle to more ductile (W. Wang et al., 2023). However, this increase in toughness is not always accompanied by an increase in compressive strength; some studies report a slight decrease in compressive strength due to the formation of microvoids or uneven fiber distribution. This suggests that biomass fibers are more appropriately positioned as elements that enhance ductility and energy dissipation rather than simply increasing compressive strength.

Based on a comparative analysis of various fiber types, this study formulated a conceptual model of a zoned hybrid composite that divides the mechanical functions of the material into three main zones: a core zone as the center of ductility and energy dissipation, a transition zone as an interface reinforcement, and an external lamination zone as a flexural control and crack opening limiter. This approach aligns with the development direction of *fiber-reinforced geopolymer composites* that combine environmental sustainability with structural performance by optimizing fiber function placement within the cross-section (Abbas et al., 2022). The composite development model produced in this study consists of three subsystems that work simultaneously in the face of earthquake loading: (1) a geopolymer-based core zone with high-ductility fibers such as bamboo or hemp to maximize energy dissipation; (2) a transition zone as a stress distribution stabilizer to prevent interlayer slippage; and (3) an external lamination zone using jute or ramie to increase flexural capacity and limit crack opening. This three-zone formulation is a major contributor because it offers a more comprehensive hybrid configuration than the single-fiber or simple lamination models dominant in previous studies. To clarify the scientific basis for the functional division of each fiber, Table 1 presents a synthesis of the main mechanical performance, limitations, and

implications for the design of earthquake-resistant hybrid composites.

**TABLE 1. BIOMASS FIBER PERFORMANCE SYNTHESIS AND ITS IMPLICATIONS FOR EARTHQUAKE-RESISTANT HYBRID COMPOSITES**

Types of Fiber	Findings mechanical main	Limitations	Implications design
Bamboo	High tensile & flexural strength, increasing ductility and changing the failure mode to less brittle (Lin et al., 2024)	Very sensitive to moisture and fiber treatment quality	Core strengthening (matrix concrete/geopolymer) for ductility and <i>post-crack bridging</i> .
Hemp	Ductility height and retention deformation repetitive Enough stable (Saini et al., 2024)	Variation in quality between regions and fiber orientation	Dispersion 0.5–2% vol as dissipation core energy
Jute	Flexural performance superior as a woven laminate, increasing capacity flexibility and control cracked surface (Saini et al., 2024)	Potential delamination when resin bond no adequate	External lamination (1–3 layers) for crack opening control
Ramie	Energy absorption in both cyclic loads and thin structures (W. Wang et al., 2023)	Susceptible to moisture degradation without treatment	Thin overlay layer for lateral deformation mitigation
Sisal	Helps control initial cracking and provides thermal stability (Saini et al., 2024)	Tends to be brittle under high load cycles	Amplifier secondary on lamination external
Tree fiber dates/similar agro -fibers	High initial energy absorption and increased concrete toughness (W. Wang et al., 2023)	Relatively low fatigue life at high cycles	Shock absorbing zone, not the main load-carrying element
Straw & agro waste (corn straw, etc.)	Improving fatigue resistance and bonding in pozzolan/geopolymer-based matrices (Abbas et al., 2022)	Heterogeneity of fiber size and quality	Biomass-based geopolymer core candidates
Kenaf	Lightweight, increased flexural toughness at moderate loads (Saini et al., 2024)	Durability against moisture is still limited	Alternative for light retrofit with surface protection

Table 1 shows that bamboo occupies a unique position as a biomass fiber capable of providing significant increases in tensile and flexural strength while changing the failure mode from brittle to more ductile, especially when mixed in a concrete matrix or other cementitious materials. (Lin et al., 2024) . However, almost all studies emphasize the importance of fiber treatment and moisture control, so using bamboo as a core reinforcement requires a low-permeability matrix design, such as geopolymer or concrete with a strict water-binder ratio. This reinforces the logic that the core zone of hybrid composites needs to use bamboo fiber (or similar fibers) that are treated and dispersed in a controlled manner to maximize energy dissipation.

At the same time, a review of the use of jute, ramie, sisal, and kenaf in the context of civil structures shows that these fibers are more effective when applied as polymer composites or external laminates, rather than simply mixed in mortar (Saini et al., 2024). As *woven laminates*, jute and ramie contribute

significantly to increasing flexural capacity and controlling crack opening in the tensile zone of the surface of structural elements. However, the success of this role depends on the quality of the resin bond, surface preparation, and curing procedures, so the external laminate zone in hybrid composite models must be designed with clear application protocols, especially in retrofit scenarios.

Straw fiber, wood waste, and other agro-fibers combined with pozzolan- or geopolymer-based matrices strongly indicate that local biomass waste can be utilized as a core reinforcement component, contributing to structural toughness while reducing the material's carbon footprint (Abbas et al., 2022). Studies on mortar and concrete reinforced with wood waste and plant fibers have shown increased energy absorption capacity and crack resistance, although controlling fiber uniformity and mixing quality remains a challenge. In the developed model, these fiber types are more relevant when placed in the core zone in combination with primary fibers such as bamboo or hemp to maximize ecological benefits.

From the matrix side, a series of reviews on fiber-reinforced geopolymer composites concluded that geopolymers provide an attractive platform for environmentally friendly composites due to their lower CO<sub>2</sub> emissions, good chemical resistance, and ability to bind various types of fibers (Abbas et al., 2022; Ranjbar & Zhang, 2020). In addition , the mechanism microstructure geopolymer reinforced fiber proven increase capacity absorption energy and material toughness through increased bonding and bridging cracked (Baskar et al., 2023).

However , there are sensitivity to design mixed , type activator , and the water–binder ratio that can influence ability bond as well as cracked shrinkage , so that validation design composite need consider durability and stability cyclic term long (Qin et al., 2023). This create a hybrid composite core zone based on geopolymer need designed with consider balance between workability, strength beginning, and ability withhold cracked when fiber experience dispersed.

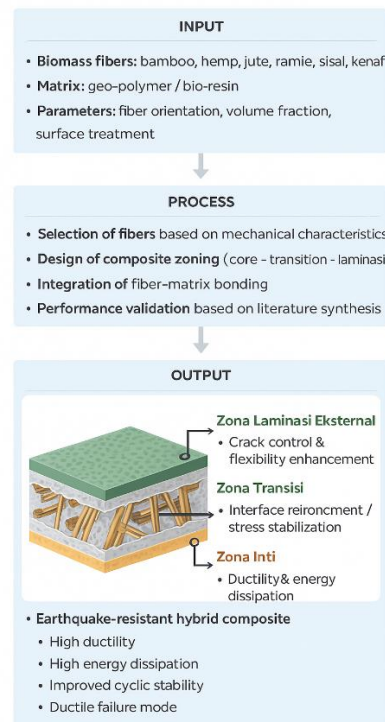


Figure 1. Conceptual Model Development Biomass Fiber - Based Hybrid Composites with Zoning Function Mechanic for Earthquake Resistant Structure

The visualization in Figure 1 confirms that distribution function mechanic through core zoning – transition – laminate allows mechanism dissipation energy and control cracked Work in a way simultaneous during loading earthquake. Implications practical from the conceptual model This appears in two scenarios main implementation in the field, namely construction new and retrofit structures existing. For construction new, fiber bamboo, hemp, or fiber agriculture other can mixed direct to in matrix geopolymer for create the core element more structural ductile and capable absorb energy earthquake. For structure existing, layer jute or ramie laminate with resin matrix or thin geopolymer can applied as system *jacketing* or *wrapping* For increase resilience flexible and controlling development cracked without add burden dead in a way significant (Saini et al., 2024). Approach This in line with trend use composite fiber experience in strengthening reported structural in various studies applied.

However thus, durability still become issue critical in adoption composite based fiber biomass. Review latest about NFRC limitations highlighted problem water absorption, degradation interface fiber – matrix, and decrease characteristic mechanic consequence cycle repeated loads and humidity (W. Wang et al., 2023). Because that, the conceptual model developed need followed with clear mitigation strategies, such as alkali and silane treatment of fiber, addition layer protector hydrophobic in the lamination zone external, as well as testing *aging* and cycle wet – dry stage validation experimental next.

In a way overall, results and discussion This show that development of composite materials friendly environment based fiber biomass for application structure technique civilians in the area vulnerable earthquake more appropriate viewed as a design process systemic than just replacement fiber synthetic with fiber natural. Combination mapping function fiber, selection matrix sustainable like geopolymers, and zoning strategies mechanic allows achievement balance between ductility, dissipation energy, capacity flexible, and sustainable environment (Olanrewaju et al., 2025). The resulting conceptual model become strong foundation For study advanced in the form of testing laboratory, modeling numeric nonlinear, and studies eligibility economy – environment before implementation area of buildings in disaster-prone areas earthquake (Ntsie et al., 2025).

#### IV. CONCLUSION

Study This conclude that hybrid composite based fiber biomass own potential strong as alternative structural materials sustainable for construction in disaster-prone areas earthquake. Synthesis literature show that zoning strategy function with put fiber modulated ductility and dissipation energy high in the core as well fiber controller cracks in the laminate zone external capable increase response structural to loading cyclic. Matrix integration geopolymer the more strengthen performance composite through bond good chemistry, durability high, and emissions more carbon low, so that make design This worthy in a way technical and ecological for building stand earthquake.

Study advanced recommended for validate the conceptual model This through testing mechanic basic, element test scale with loading monotonic and cyclic, as well as modeling numeric nonlinear to understand phenomenon cracking and sensitivity of design parameters. Evaluation durability and analysis recycling life required for ensure reliability term length and eligibility environment, while analysis cost - benefit required before implementation scale field. Compilation standard fabrication and protocols control quality expected can

push adoption wide hybrid composite based biomass as a safe and sustainable structural material.

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