Seshat’s Bones: A Monolithic, Isotropic Nanocomposite Derived Entirely from *Cannabis Sativa L. (Hemp)*

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Abstract

This paper details the theoretical framework for "Seshat’s Bones," a fully isotropic, monolithic nanocomposite derived entirely from *Cannabis sativa L.*. This advanced material eschews traditional fiber reinforcement in favor of a high-density, multi-scale particulate system fully integrated within a bio-epoxy matrix. The formulation consists of an epoxidized hemp oil (EHO) matrix heavily loaded with a hierarchical system of pyrolyzed hemp biochar micro-particles and surface-functionalized hemp-derived carbon nanosheets (HD-CNS). Modified hemp lignin serves as a critical bio-compatible interfacial agent to ensure covalent bonding throughout the matrix. The resulting material is designed to be castable or compression-moldable, producing a dense, void-free solid with uniform properties in all directions. It is hypothesized that this approach will yield a material with performance characteristics competitive with castable metals and technical ceramics, while being fully bio-based and sustainable.

Keywords: Isotropic Composite, Particulate Reinforcement, Nanocomposite, *Cannabis sativa*, Compression Molding, Sustainable Materials.

Contents

1 Introduction

The relentless pursuit of high-performance materials in the modern era has historically gravitated towards systems optimized for specific directional strengths, often achieved through fiber reinforcement. While highly effective for applications where loads are primarily uniaxial or biaxial, such anisotropic materials inherently possess directional weaknesses and present significant manufacturing challenges when complex geometries are required [5]. This paper introduces a groundbreaking paradigm shift in material design: "Seshat's Bones," a fully isotropic, monolithic composite. In this novel material system, mechanical strength is not contingent upon the preferential alignment of reinforcing fibers but is instead an intrinsic and uniform property derived from the meticulously engineered matrix itself.

The foundational principle of the "Seshat's Bones" formulation lies in achieving an ultra-dense and exceptionally homogenous dispersion of multi-scale particulates. Through precise engineering of the particle-matrix interfaces at the molecular level, this system is designed to emulate the remarkable structural integrity observed in highly optimized natural materials such as bone or nacre. These natural analogues derive their extraordinary toughness, strength, and damage tolerance from intricate internal micro-architectures, where hierarchical structures and sophisticated interfacial interactions play a crucial role. By mirroring these biological strategies, "Seshat's Bones" aims to achieve exceptional mechanical performance, characterized by an inherent toughness stemming from its complex, multi-component internal structure, thereby offering a truly isotropic solution for advanced material applications.

2 Materials and Proposed Methodology

The development of "Seshat's Bones" hinges on the synergistic integration of several key components, all derived from *Cannabis sativa L.*, ensuring a fully bio-based and sustainable material system. The proposed methodology encompasses the detailed synthesis and functionalization of these components, followed by a robust fabrication process designed to achieve a dense, void-free monolithic composite.

2.1 Component Synthesis and Functionalization

The meticulous preparation and surface modification of each constituent are critical for achieving the desired isotropic properties and robust interfacial bonding within the composite.

- **Epoxidized Hemp Oil (EHO) Matrix:** The primary polymer matrix will be synthesized via the epoxidation of cold-pressed hemp seed oil. This process involves the conversion of carbon-carbon double bonds in the unsaturated fatty acid chains of the oil into epoxide rings. The epoxidation of vegetable oils, including soybean and linseed oil, is a well-established industrial process that yields reactive precursors suitable for thermosetting polymer matrices [1]. The resulting EHO will serve as the foundational resin, providing the continuous phase that encapsulates and binds the particulate reinforcement system.

- **Multi-Scale Particulate Reinforcement System:** To achieve broad mechanical reinforcement across different length scales and ensure isotropic properties, a dual-scale particulate system is proposed.

  - *Micro-filler: Pyrolyzed Hemp Biochar:* Biochar derived from the pyrolysis of hemp biomass (e.g., hurds or stalks) will be utilized as the micro-filler. These particles, with an average size of less than $50\,\mu$m, will be incorporated at a high volume fraction, typically between 30-40%. Biochar's high carbon content, porous structure, and inherent rigidity contribute significantly to enhancing the compressive strength and thermal stability of polymer composites. Its effectiveness as a reinforcing filler in various thermoset systems has been extensively documented [2]. The particle size distribution will be carefully controlled to optimize packing density and minimize void formation.

  - *Nano-reinforcement: Hemp-Derived Carbon Nanosheets (HDCNS):* For nano-scale reinforcement, Hemp-Derived Carbon Nanosheets (HDCNS) will be employed. These nanosheets, analogous to graphene or few-layer graphene, can be produced through the catalytic pyrolysis of specific biomass precursors [4]. The HDCNS will be critically surface-functionalized with carboxyl groups (-COOH). This functionalization is paramount as it facilitates robust covalent bonding with the epoxide rings of the EHO matrix during curing, thereby ensuring efficient stress transfer and preventing agglomeration of the nanoparticles, which is a common challenge in nanocomposites. The high aspect ratio and exceptional mechanical properties of HDCNS are expected to contribute significantly to the overall stiffness and toughness of the composite.

- **Bio-Interfacial Agent: Modified Hemp Lignin:** Lignin, a complex amorphous polymer rich in aromatic units, will be extracted from hemp hurd. This extracted lignin will undergo chemical modification to enhance its dispersibility within the EHO matrix and to serve as a compatibilizer between the EHO and the particulate fillers. Specifically, lignin can be functionalized with reactive groups that can participate in the curing reactions of the epoxy or form strong intermolecular interactions with the filler surfaces. The strategic use of modified lignin is a well-recognized strategy in the field of advanced bio-composites for improving particle-matrix adhesion and overall mechanical performance [3]. This agent is crucial for ensuring a truly monolithic structure by minimizing interfacial weaknesses.

- **Cross-Linking Agent: Bio-Anhydride Hardener (Azelaic Anhydride):** The polymerization and cross-linking of the EHO matrix will be initiated by a bio-anhydride hardener, specifically Azelaic Anhydride. This compound can be synthesized from hemp oil fatty acids, maintaining the fully bio-based nature of the system. Dicarboxylic acid anhydrides are widely recognized and highly effective curing agents for epoxy resins, known for producing high-performance thermosets with excellent thermal and mechanical properties. The anhydride reacts with the epoxide rings to form ester linkages, creating a dense, three-dimensional polymer network.

2.2 Monolithic Composite Fabrication

The proposed fabrication process is designed to produce a dense, void-free, and homogeneously reinforced solid part, leveraging the advantages of compression molding for high-volume fraction particulate composites.

1. **Slurry Preparation:** A high-viscosity slurry will be meticulously prepared by mechanically blending the pre-synthesized EHO, modified lignin, pyrolyzed hemp biochar, functionalized HDCNS, and the bio-anhydride hardener. This blending will be performed using a high-shear planetary mixer to ensure a homogeneous dispersion of all particulate fillers within the resin, minimizing agglomeration and ensuring uniform distribution.

2. **Degassing:** The homogenous slurry will then be subjected to a rigorous degassing process under high vacuum. This critical step is essential to eliminate all entrapped air bubbles and

volatile components, which, if present, could lead to macroscopic voids and significantly compromise the mechanical integrity and density of the final composite.

3. **Mold Charging:** The degassed slurry, now a viscous paste, will be carefully poured or charged into a pre-heated steel mold. The mold design will be optimized for the desired final part geometry, and its heated state will facilitate the flow and compaction of the slurry.

4. **Compression Molding:** The charged mold will be strategically placed within a hydraulic press. A controlled pressure, typically in the range of 10-15 MPa, will be applied while the mold is simultaneously heated through a precisely controlled thermal cycle. The combined effect of heat and pressure ensures complete mold filling, promotes intimate contact between the matrix and fillers, and drives the initial stages of the curing reaction, leading to a highly dense and consolidated composite.

2.3 Curing Protocol

A pressure-assisted, multi-stage curing process is essential to achieve maximum cross-link density, optimal mechanical properties, and a high glass transition temperature (T_g) for the "Seshat's Bones" material.

- **Initial Cure:** Under applied pressure within the hydraulic press, the temperature will be ramped to approximately $90\,^{\circ}\mathrm{C}$ and held for a period of 3 hours. This initial cure stage facilitates the primary cross-linking reactions, allowing the resin to gel and solidify while maintaining the compacted state under pressure, preventing void formation and ensuring dimensional stability.

- **Post-Cure:** Following the initial cure, the temperature will be further ramped to $150\,^{\circ}\mathrm{C}$ and held for an additional 2 hours. This post-cure stage is critical for driving the epoxy-anhydride reactions to near completion, maximizing the degree of cross-linking. This elevated temperature ensures the development of the ultimate network structure, leading to the highest possible mechanical strength, stiffness, and glass transition temperature (T_g), thereby optimizing the material's performance under various service conditions.

3 Anticipated Characterization and Properties

The unique isotropic formulation of "Seshat's Bones" is expected to yield distinctive material properties, contrasting sharply with traditional anisotropic composites. Rigorous characterization will be paramount to validate the theoretical framework and confirm the desired performance attributes.

- **Morphology:** Scanning Electron Microscopy (SEM) of the fracture surfaces will be a primary tool for morphological characterization. SEM images are expected to reveal a dense, homogeneous, and glassy polymer matrix with a remarkably uniform dispersion of both micro-scale biochar particles and nano-scale HDCNS. Crucially, the absence of macroscopic voids and agglomerations will indicate successful processing. The fracture appearance is anticipated to be quasi-brittle, a characteristic often observed in highly cross-linked thermosets. However, detailed examination should reveal clear evidence of micro-scale toughening mechanisms. Specifically, features such as crack deflection around the biochar particles and localized micro-crack pinning by the HDCNS are key mechanisms for energy dissipation in particulate composites and will contribute to the overall toughness of the material [5]. The integrity of the particle-matrix interface will also be evident, with strong adhesion preventing premature debonding.

- **Mechanical Performance:**
  - *Tensile Properties:* Tensile testing, conducted according to standards such as ASTM D638 for plastics, is predicted to demonstrate high modulus (stiffness) and high strength. A critical validation point will be the uniformity of these properties in all testing directions (e.g., parallel and perpendicular to the molding direction if a distinct "flow" exists, though an isotropic material should not show significant differences). This directional independence is the hallmark of an isotropic material.
  - *Compressive Strength:* The material is expected to exhibit exceptional compressive strength. This attribute will be primarily due to the high volume fraction of rigid biochar micro-particles, which are inherently strong in compression and effectively bear compressive loads within the composite.
  - *Toughness:* While quasi-brittle, the engineered multi-scale reinforcement and robust interfaces are hypothesized to impart significant toughness compared to unreinforced epoxy. This will be assessed through fracture toughness tests, looking for evidence of increased crack propagation resistance.
  - *Hardness and Abrasion Resistance:* The dense packing of hard particulate fillers within a stiff polymer matrix should also translate to high surface hardness and good abrasion resistance, making it suitable for wear-prone applications.

The primary advantage of this "Seshat's Bones" architecture lies in its inherent homogeneity and isotropy. As an isotropic material, its performance under various loading conditions is predictable, irrespective of the direction of the applied stress. This characteristic makes it exceptionally well-suited for complex, multi-axial load-bearing applications where traditional anisotropic materials would exhibit critical weaknesses or require intricate design considerations to account for directional variability. In this regard, "Seshat's Bones" is designed to perform similarly to engineered isotropic materials such as cast aluminum or steel, but with the added benefits of sustainability and bio-compatibility.

4 Conclusion

The theoretical evolution of the "Seshat's Bones" concept into a fully monolithic particulate nanocomposite represents a significant advancement in the realm of sustainable high-performance materials. By deliberately departing from traditional fiber reinforcement strategies, we propose a material system that is inherently highly moldable, offers true isotropic mechanical properties, and derives its structural integrity from precisely engineered interactions at both the molecular and micro-scale levels. This theoretical framework, rigorously supported by established principles in polymer science, composite mechanics, and biomass utilization, provides a clear and viable pathway to a new class of sustainable materials. These materials are envisioned to exhibit performance characteristics competitive with conventional engineered metals or ceramics, yet are sourced entirely from a single, renewable agricultural crop, *Cannabis sativa L.*. The successful realization of "Seshat's Bones" would not only provide a high-performance, eco-friendly alternative for diverse engineering applications but also significantly contribute to the circular economy by valorizing agricultural waste streams into advanced materials.

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